BSR 4175

Laser Geodynamic Satellite Thermal/Optical/Vibrational Analyses and Testing

Final Report Addendum

Volume II
Technical Report

Book 1

(NASA-CR-120755) LASER GEODYNAMIC SATELLITE THERMAL/OPTICAL/VIBRATIONAL ANALYSES AND TESTING, VOLUME 2, BOOK 1 TECHNICAL REPORT Final Report (Bendix Corp.) 214 p HC $7.25 CSCL 17H G3/35
N75-23934
Unclas
22393

DR No. MA-04
DPD No. 296

Contract NAS 8-30658

January 1975

Prepared for:

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Bendix Aerospace Systems Division

Ann Arbor, Michigan

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FOREWORD

This technical report presents the results of a retroreflector performance improvement program, conducted as part of the LAGEOS Phase B Thermal/Optical/Vibration Analyses and Test Program. The study was conducted by The Bendix Corporation, Aerospace Systems Division, for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, under Contract NAS 8-30658.

The results of this study are contained in two volumes, which are prepared and submitted in accordance with the data requirements of Contract NAS 8-30658, as follows:

Volume I	Executive Summary
Volume II	Technical Report

The study effort was initiated in September 1974 and the technical effort was completed in December 1974. The study was conducted under the direction of Mr. C. W. Johnson, LAGEOS Program Manager at NASA/MSFC and Mr. J. M. Brueger, LAGEOS Program Manager at Bendix Aerospace Systems Division.

As in the initial study phase, the successful completion of this study effort was the result of the close cooperation and conscientious support of the various individual government and contractor representatives involved. In particular, the efforts of the following is acknowledged: J. Zurasky and J. Randall of NASA/MSFC, D. Arnold of SAO, E. Granholm, J. Monroe and C. Sheppy of Bendix, C. Zanoni and S. Laufer of Zygo, M. Rimmer and R. Byrd of Itek and W. Augustyn of Perkin-Elmer. In addition to his support in the overall Study, Mr. Zurasky was responsible for the MSFC study of the effect of laser wavelength on dihedral angle selection, the results of which are included in this report.

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VOLUME II

TECHNICAL REPORT

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

1.0 INTRODUCTION

This report, an addendum to the basic LAGEOS Phase B Final Report (Bendix document BSR 4159), describes the results of a 4-month add-on study effort, conducted for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center from September 1974 through January 1975. The add-on study effort, which evolved from the results of the basic study analyses and testing efforts, sought to resolve a theoretical/test data paradox, the solution of which was also expected to identify a LAGEOS retroreflector design change for optical performance improvement.

The basic study analyses and test results, as presented in the LAGEOS PDR in September 1974 and described in the LAGEOS Phase B Final Report (BSR 4159), indicated a paradox between the theoretical optical performance, as initially expected from geometric predictions for the nominal retroreflector dihedral angle, and the empirical optical performance, based on photometric measurements made directly in the return beam far-field diffraction pattern of the LAGEOS test retroreflectors. Predicted optical performance, as obtained from an ITEK retroreflector math-model and ray-trace analysis, was between the geometric predictions and the far-field diffraction pattern test measurements. The direct impact of this paradox on LAGEOS was the expectation that retroreflector optical performance could be improved by the specification of the optimum dihedral angle, as determined and verified by additional analysis and test.

This volume contains the technical results of the study, organized by task areas. The interrelationships of these tasks are also described and the major study decisions are identified.

2.0 STUDY PROGRAM SUMMARY

The overall purpose of this effort was achieved through the accomplishment of the following specific study objectives:

- Determine the basis of the already-demonstrated retroreflector optical performance, through the evaluation of measurement, analysis and test data for the existing LAGEOS retroreflectors.
- Identify the dihedral angle specification changes for retroreflector performance improvement, on the basis of predicted optical performance.
- Verify the retroreflector optical performance improvement by analysis and test.

Based on interferogram analysis, the original LAGEOS test retroreflectors were found to have an average dihedral angle of about $90^{\circ} + 1.8$ arc sec. Some of the mechanical measurement data tended to confirm this result, although the wide variation between mechanical measurements reduced the confidence in this form of dihedral angle determination. From the analysis of perfect retroreflectors, peak energy was expected to occur at $90^{\circ} + 1.35$ arc sec for the LAGEOS far-field annulus. The effect of dihedral angle tolerance, however, was to spread the energy distribution which led to the initial prediction of optimum energy dihedral angle at $90^{\circ} + 1.25$ arc sec. Test data for the original retroreflectors tended to confirm this conclusion.

Subsequent tests and evaluation of LAGEOS test retroreflectors, reworked to smaller dihedral angles, confirmed the initial prediction of optimum energy at a dihedral angle of $90^{\circ} + 1.25$ arc sec. Analysis by NASA/MSFC, included in this report, also concluded that this nominal dihedral angle was optimum for other laser beam wavelengths.

The study was conducted by the accomplishment of a number of tasks, as diagrammed in Figure 2-1, which were intended to provide the technical results to meet the program objectives. The Zygo Corporation and the Itek Corporation, under Bendix direction, supported the performance of these tasks.

- Task 1 - Retroreflector Dimensional Verification. New Twyman-Green interferograms were generated by Itek for each of the original six (6) LAGEOS test retroreflectors and an analysis

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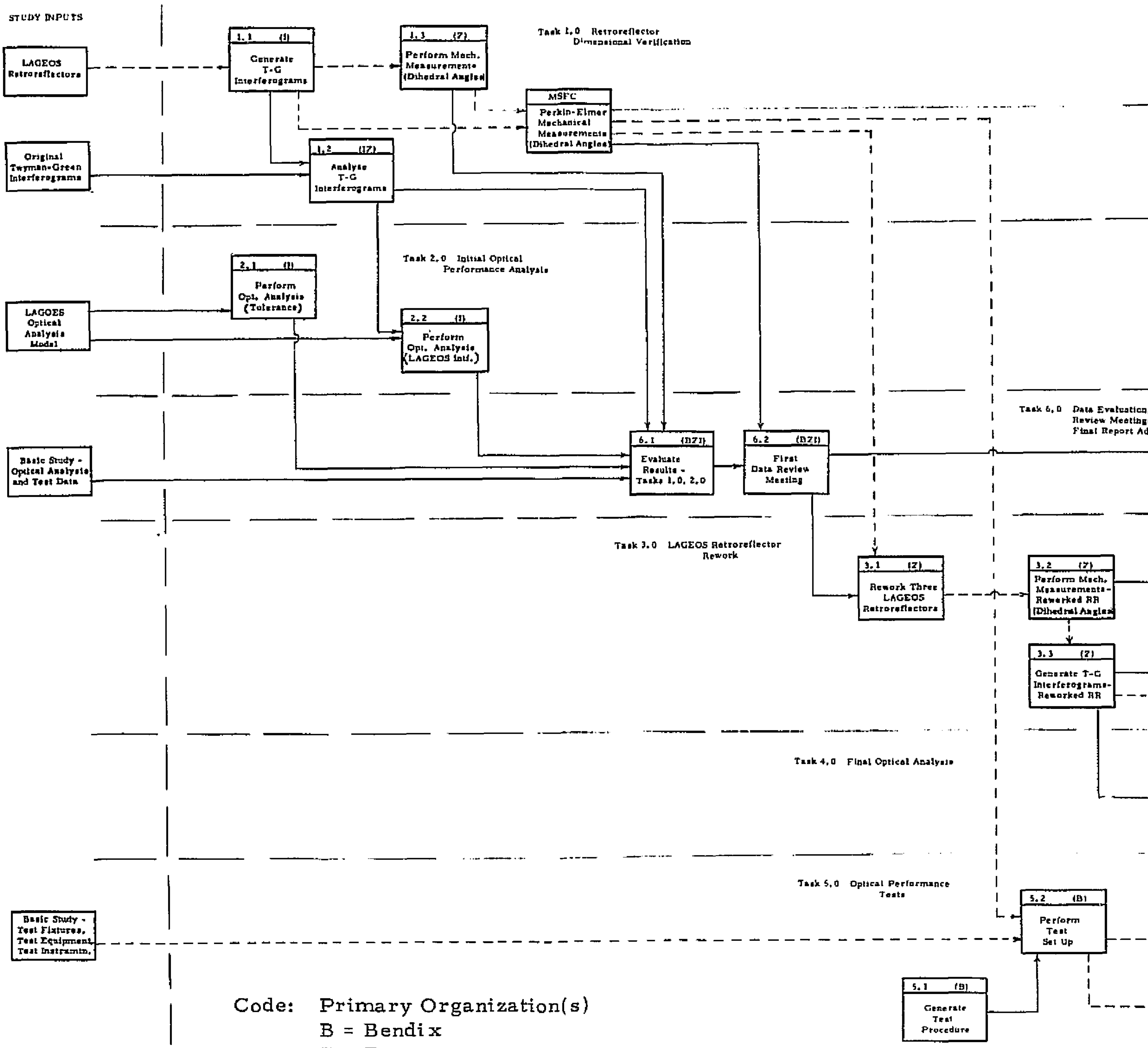


Code: Primary Organization(s)
B = Bendix
Z = Zygo
I = Itek

———— Data Flow

--------- Hardware Flow

Figure 2-1 LAGEOS Retroreflector

2

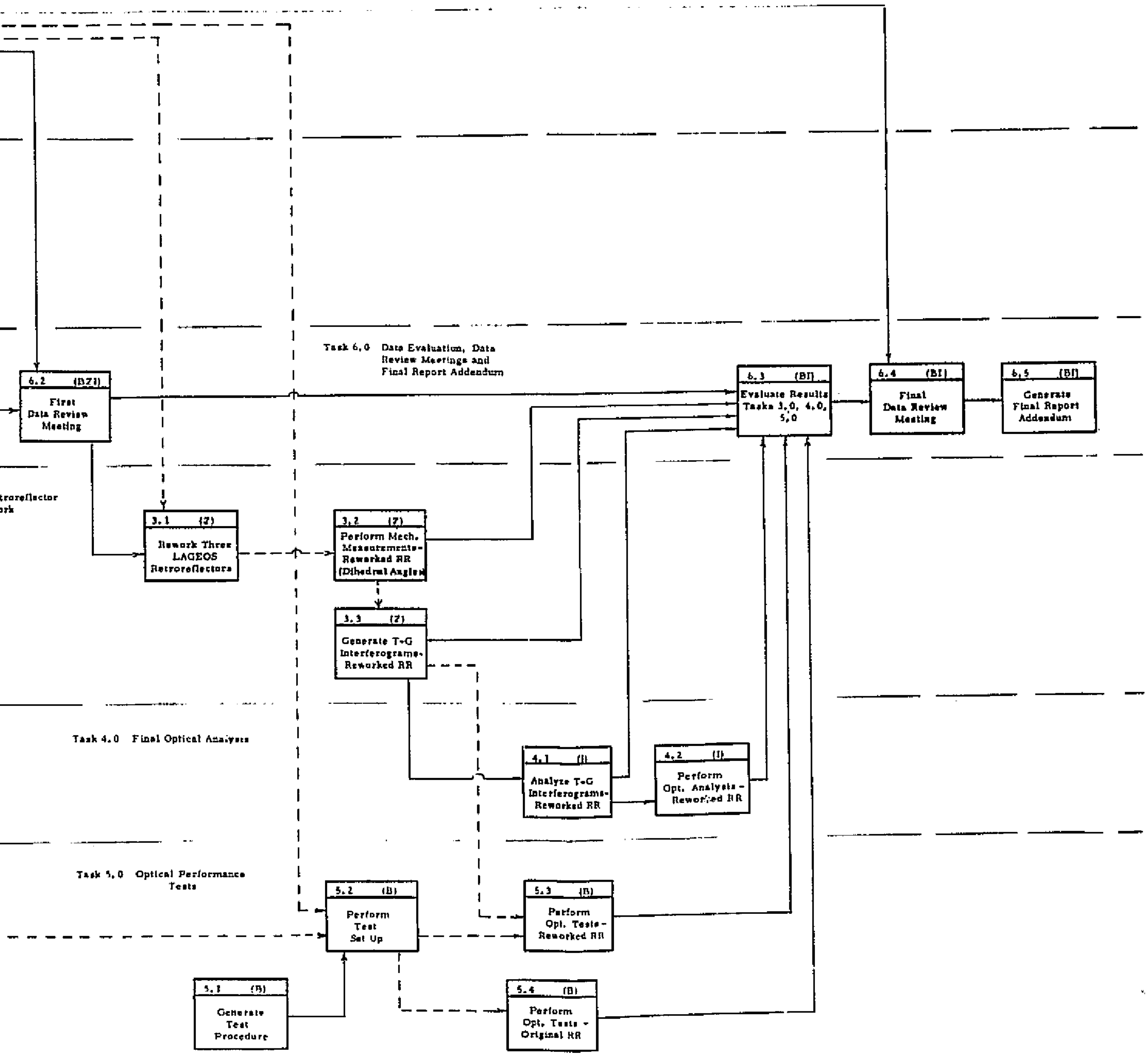


Figure 2-1 LAGEOS Retroreflector Improvement Study Logic Network

was performed to determine the emerging wavefront relative angles and the related dihedral angles from these interferograms. In addition, the existing interferograms for these retroreflectors, generated during the basic program, were analyzed by Zygo and Itek in the same fashion.

Mechanical measurements were performed on three (3) of the original LAGEOS test retroreflectors to redetermine, in a more rigorous manner, the measured dihedral angles. Independent measurements were made by Zygo, the Moore Special Tool Company and Perkin-Elmer.

- Task 2 - Initial Optical Performance Analysis. Far-field diffraction pattern optical performance predictions were generated by Itek for each of three (3) "perfect" LAGEOS retroreflectors, having equal nominal dihedral angles of 90° + 0.9 arc sec, 90° + 1.25 arc and 90° + 1.75 arc sec, respectively. This data, together with data previously generated for 90° + 1.5 arc sec and 90° + 2.1 arc sec, dihedral angles, was used to show the effects of average dihedral angle on the performance of nominal retroreflectors. Performance predictions were also generated for a LAGEOS retroreflector having off-nominal dihedral angles of 90° + 0.4 arc sec, + 0.9 arc sec and 1.4 arc sec. This data, together with previously-generated data for two other sets of off-nominal dihedral angles, was used to show the effects on performance of average dihedral angle for off-nominal retroreflectors.

  The wavefront data, generated in the interferogram analysis of six (6) original LAGEOS test retroreflectors, was used to generate far-field diffraction pattern optical performance predictions for these actual LAGEOS test retroreflectors.

  Differences between the Smithsonian Astrophysical Observatory (SAO) retroreflector math-model results and the Itek retroreflector math-model results were also resolved as part of this task.

- Task 3 - LAGEOS Retroreflector Rework. Three (3) LAGEOS retroreflectors, selected in the First Data Review Meeting, were reworked by Zygo to incorporate the dihedral angles selected in the same meeting. Dihedral angles were measured mechanically and Twyman-Green interferograms were generated for each reworked retroreflector.

- Task 4 - Final Optical Performance Analysis. The interferograms for the reworked retroreflectors were analyzed by Itek to determine emerging wavefront relative angle and the related dihedral angles.

  Far-field diffraction pattern optical performance predictions were generated for each of the reworked retroreflectors.

- Task 5 - Optical Performance Tests. Optical tests were performed by Bendix to obtain far-field diffraction pattern data for the reworked retroreflectors. Tests were also run for the remaining three (3) original retroreflectors to provide a baseline check. Tests were run at isothermal-ambient and isothermal-vacuum conditions. The necessary test procedures were generated and the test set-up was performed.

- Task 6 - Data Evaluation, Review Meetings and Final Report Part 1: The first part of this two-part task, followed the accomplishment of Tasks 1 and 2.

  The data evaluation included a comparison of the dihedral angle mechanical measurement results and the interferogram analysis results to evaluate measurement repeatability and validity. The correlation between the two basically-different means of determining dihedral angle was also evaluated. Dihedral angles, calculated from optical analysis and optical test results, were also included for comparison purposes.

  The far-field energy centroid of the return beam was estimated, from predicted far-field diffraction pattern data generated in the optical analysis, for each of the nominal, off-nominal and LAGEOS test retroreflectors. The evaluation included a comparison of these results with the centroid measurements made from far-field diffraction pattern photographs, taken during the optical tests of the basic program.

  The retroreflector optical performance, in terms of the relative energy in the far-field diffraction pattern annulus specified for LAGEOS and as a function of dihedral angle, was compared for the nominal, off-nominal, and LAGEOS test retroreflectors (both analytically-derived and test-derived performance data). A preliminary recommendation regarding the selection of the

LAGEOS dihedral angle resulted from the evaluation. In addition, the evaluation considered the effect of dihedral angle tolerance on performance.

As part of this effort, an optical test was conducted to determine the effect of the LAGEOS retroreflector retainer ring on the return beam relative intensity measurements.

The data results, conclusions and recommendations were presented in the First Data Review Meeting at MSFC on 24 October 1974. The meeting resulted in the selection of the dihedral angles to be incorporated in three (3) of the LAGEOS test retroreflectors.

This task was performed by the combined efforts of Zygo, Itek, and Bendix.

Part 2: This second, and final, part of Task 6 was performed after the completion of Tasks 3, 4, and 5.

The data evaluation included the comparison of the dihedral angle mechanical measurement results and the predicted dihedral angles resulting from the interferogram analysis for the reworked retroreflectors.

The far-field energy centroid of the return beam was estimated from predicted far-field diffraction pattern data, generated in the optical analysis for each of the reworked retroreflectors. These results were compared with energy centroid measurements obtained from far-field diffraction pattern photographs, taken for each reworked retroreflectors in the optical tests.

The relative energy, within the LAGEOS annulus of the return beam far-field diffraction pattern as measured in the optical tests and as predicted by the optical analysis for each reworked retroreflector, was compared with the previously-obtained performance data. The evaluation resulted in a final recommendation for the selection of the LAGEOS dihedral angle.

The data results, conclusions and recommendations were presented in the Final Data Review Meeting at MSFC on 18 December 1974. These results, and the results of an NASA/MSFC evaluation of the effects of laser beam wavelength, provided the basis for selection of the final LAGEOS dihedral angle by NASA/MSFC. Both Itek and Zygo supported Bendix in the performance of this task, including the presentations at the Data Review Meeting.

3.0 RETROREFLECTOR DIMENSIONAL VERIFICATION

To determine the basis of the retroreflector optical performance previously demonstrated in the basic study program, the dihedral angles of the six (6) original LAGEOS test retroreflectors were determined by mechanical measurement and by the analysis of Twyman-Green interferograms.

3.1 Interferogram Analysis

Interferograms were generated by Itek for each of the original six LAGEOS test retroreflectors. A Twyman-Green interferometer, as shown in Figure 3-1, was used to generate these interferograms for each retroreflector. Each interferogram was based on a set-up by which the resulting fringes were made perpendicular to a real edge. All resulting interferograms are shown in Appendix E of this report. No reflective coating was applied to the retroreflectors for the generation of these interferograms (i.e., they were uncoated, as in the flight design).

These interferograms were then analysed by Itek to obtain a set of dihedral angles for each retroreflector. The analysis technique is based on the determination of the plane wavefront of each retroreflector segment by fitting a plane through the fringe data for each segment. The dihedral angle (α) as shown in Figure 3-2, is then a geometric function of the index of refraction (n), the aperture diameter of the retroreflector (D) and the optical path differences (W) determined from the wavefront data. Details of this analysis, including the derivation of the mathematical relationships used, are described in Appendix E of this report. The results are tabulated in Table 3-1. The average value of each dihedral angle and the average dihedral angle of each retroreflector are shown, in addition to the results of the analysis of each interferogram.

The same analysis was made, by Itek, for the interferograms generated by Zygo in the basic study program. These results are summarized in Table 3-2 as the average dihedral angles for each retroreflector, and are compared with the results for the Itek interferograms and the Zygo and Moore measurements, to be described in Section 3.2

Zygo also made an analysis of the original Zygo interferograms. Their interferogram reduction involved the measurement of the angles between the fringes of diagonally-opposite segments. Results are shown in Table 3-3. These angles were then reduced to obtain an equivalent average dihedral angle for each retroreflector, using the geometric relationship shown in Table 3-4. The results for each retroreflector are shown in Table 3-4. The results are also compared with the measured diameter of the far-field energy centroid (from test photographs of the far-field patterns) in Table 3-5.

FIGURE 3-1

INTERFEROMETRY TEST SET-UP FOR LAGEOS RETROREFLECTORS

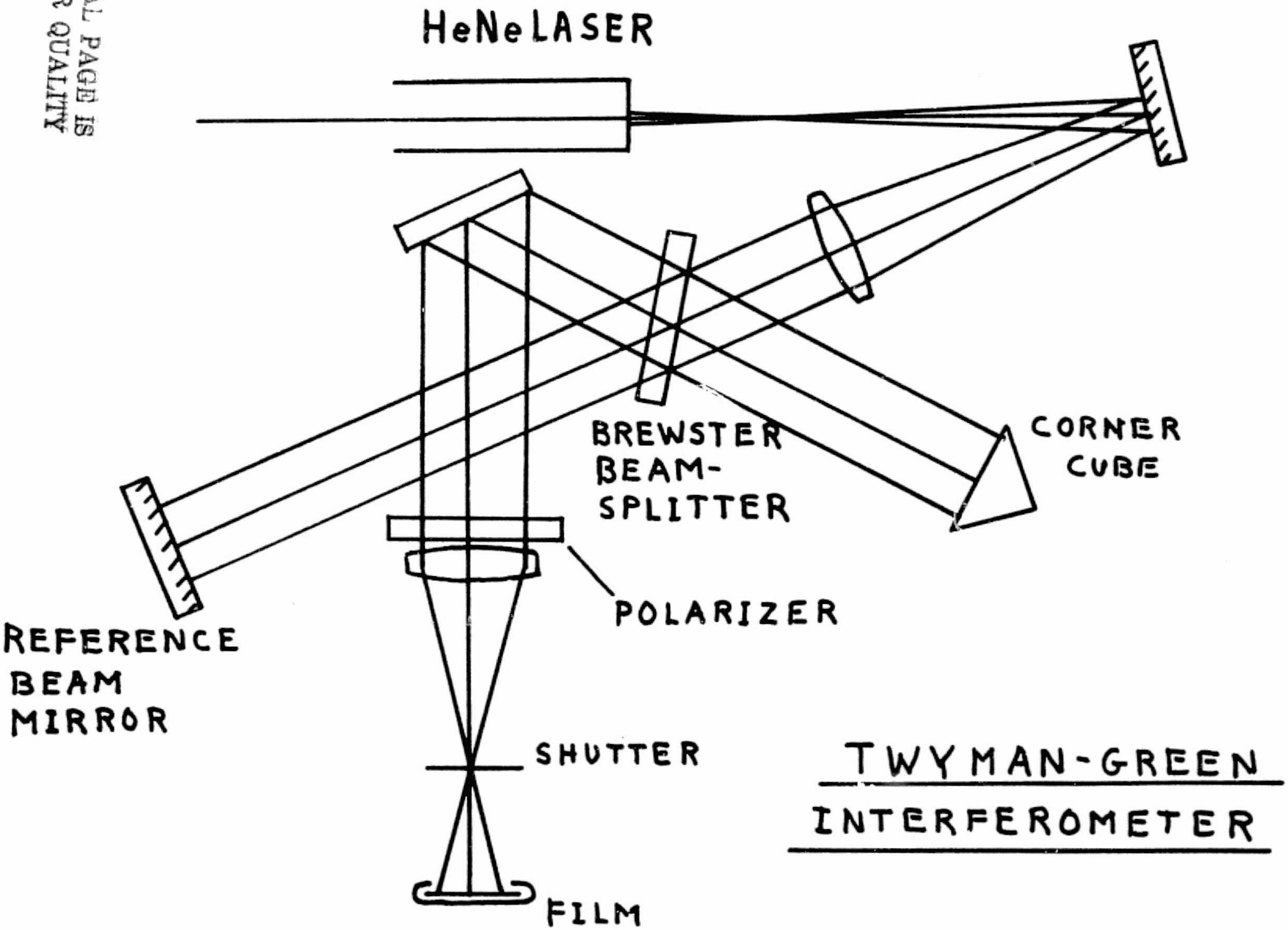
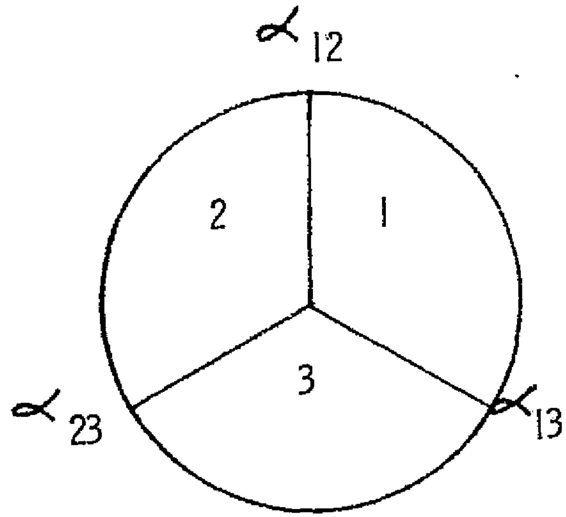
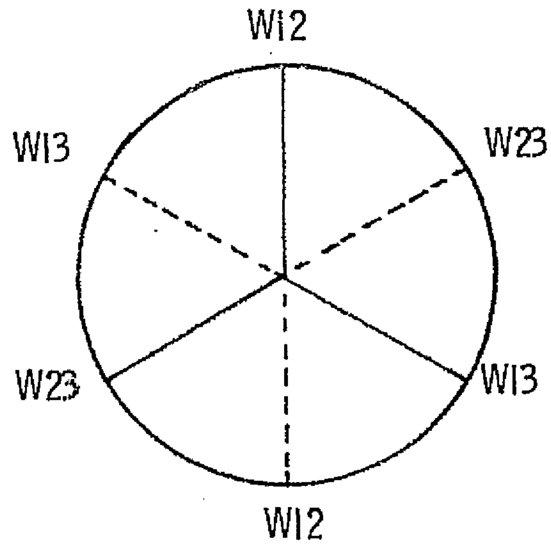


FIGURE 3-2

CALCULATION OF DIHEDRAL ANGLES FROM INTERFEROGRAM



Cube



Wavefront

$$\alpha_{12} = \frac{1}{\sqrt{2}\, nD} \left[W_{13} + W_{23} - W_{12} \right]$$

$$\alpha_{13} = \frac{1}{\sqrt{2}\, nD} \left[W_{23} + W_{12} - W_{13} \right]$$

$$\alpha_{23} = \frac{1}{\sqrt{2}\, nD} \left[W_{12} + W_{13} - W_{23} \right]$$

α = Dihedral Angle

W = Optical Path Difference (from interferogram)

n = Index of Refraction

D = Aperture Diameter

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TABLE 3-1

INTERFEROMETRIC MEASUREMENT OF DIHEDRAL ANGLES (ARC-SEC)

	INTERFEROGRAM				
Retroferflector S/N	1	2	3	Average	Av
1	1.38 1.71 1.87	1.53 1.68 2.01	1.63 1.90 1.98	1.51 1.76 1.95	1.
2	1.62 2.19 2.03	1.64 1.91 1.82	1.77 2.00 2.08	1.68 2.03 1.98	1.
3	1.32 1.30 1.61	1.30 1.38 1.59	1.38 1.53 1.53	1.33 1.40 1.58	1.
4	1.83 1.67 1.87	1.86 1.87 1.76	1.86 1.72 1.92	1.85 1.75 1.85	1.
5	2.24 2.38 2.01	2.23 2.28 1.94	2.19 2.10 1.88	2.22 2.25 1.94	2.
6	1.76 1.64 1.51	1.50 1.68 1.59	1.56 1.44 1.65	1.61 1.59 1.58	1.
				Average	1.

(1 σ = .07 ARC-SEC)

TABLE 3-2

COMPARISON OF DIHEDRAL ANGLE MEASUREMENTS

Retroreflector S/N	Moore* Mechanical	Zygo Mechanical* Operator #1	Zygo Mechanical* Operator #2	Itek Analysis: Zygo** Interferograms	Itek Analysis: Itek*** Interferograms
1	2.14	2.10	2.05	2.44	1.95
	2.00	1.67	1.89	2.04	1.76
	1.72	1.55	1.75	1.88	1.51
2	1.68	1.33	1.63	1.98	2.03
	1.84	1.38	1.81	1.76	1.98
	1.76	1.38	1.76	0.98	1.68
4	1.82	1.68	1.46	2.02	1.85
	1.80	1.24	1.30	1.31	1.75
	1.80	1.23	1.41	1.65	1.85

* The mechanically measured angles are based on five (5) measurements of each retroreflector.

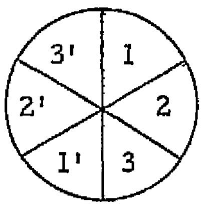
** Based on Itek analysis of one interferogram.

*** Based on Itek analysis of three interferograms.

TABLE 3-3

ZYGO INTERFEROGRAM REDUCTION DATA

Retroreflector S/N	$\phi_{11'}$ (Arc Sec)	$\phi_{22'}$ (Arc Sec)	$\phi_{33'}$ (Arc Sec)
1	17.9	21.0	18.0
2	16.0	15.2	13.3
3	17.0	13.9	11.8
4	15.2	15.7	15.6
5	23.5	21.7	18.6
6	15.5	15.4	13.4



$\phi_{nn'}$ = angle between the n and n' output wavefronts

TABLE 3-4

SUMMARY OF ZYGO INTERFEROGRAM REDUCTION RESULTS

I.

Retroreflector S/N	$(\phi_{11'} + \phi_{22'} + \phi_{33'})/3$ (arc sec)	Equivalent Average Dihedral Angle*
1	18.97	2.00
2	14.81	1.55
4	15.47	1.63
3	14.23	1.50
5	21.27	2.24
6	14.77	1.55
	Avg.	1.75

II. Average $\phi_{nn'}$ for all 3 retroreflectors = 16.59 arc sec.

III. Equivalent Average Dihedral Angle = 1.75 arc sec.

* Based on $\langle \phi_{nn'} \rangle = 4N\left(\frac{8}{3}\right)^{1/2}$ (Average Dihedral Angle), or where N = refractive index

$$\langle \phi_{nn'} \rangle = 9.51 \times \text{(Average Dihedral Angle)}$$

for fused silica

TABLE 3-5

COMPARISON OF FFDP DATA

AND

ZYGO INTERFEROGRAM REDUCTION

Retroreflector S/N	Interferogram Reduction Data	Diameter of FFDP Centroid
1	$\phi_{11'}$ = 17.9 arc sec $\phi_{22'}$ = 21.0 arc sec $\phi_{33'}$ = 18.0 arc sec	22.0 arc sec
2	$\phi_{11'}$ = 16.0 arc sec $\phi_{22'}$ = 15.2 arc sec $\phi_{33'}$ = 13.3 arc sec	19.8 arc sec
3	$\phi_{11'}$ = 17.0 arc sec $\phi_{22'}$ = 13.9 arc sec $\phi_{33'}$ = 11.8 arc sec	17.6 arc sec
4	$\phi_{11'}$ = 15.2 arc sec $\phi_{22'}$ = 15.7 arc sec $\phi_{33'}$ = 15.6 arc sec	20.6 arc sec
5	$\phi_{11'}$ = 23.5 arc sec $\phi_{22'}$ = 21.7 arc sec $\phi_{33'}$ = 18.6 arc sec	23.5 arc sec
6	$\phi_{11'}$ = 15.5 arc sec $\phi_{22'}$ = 15.4 arc sec $\phi_{33'}$ = 13.4 arc sec	18.4 arc sec

$\langle \phi_{nn'} \rangle$ = 16.58 arc sec $\langle \phi \, \mathrm{FFDP} \rangle$ = 20.3 arc sec

Equiv. Dih. $\measuredangle$ = 1.74 arc sec   Equiv. Dih. $\measuredangle$ = 2.14 arc sec

Comparison of the data for average dihedral angle in Table 3-1 and 3-4 shows close correspondence. The average dihedral angle for the original retroreflectors is seen to be about 90 + 1.8 arc sec.

3.2 Mechanical Measurements of Dihedral Angles

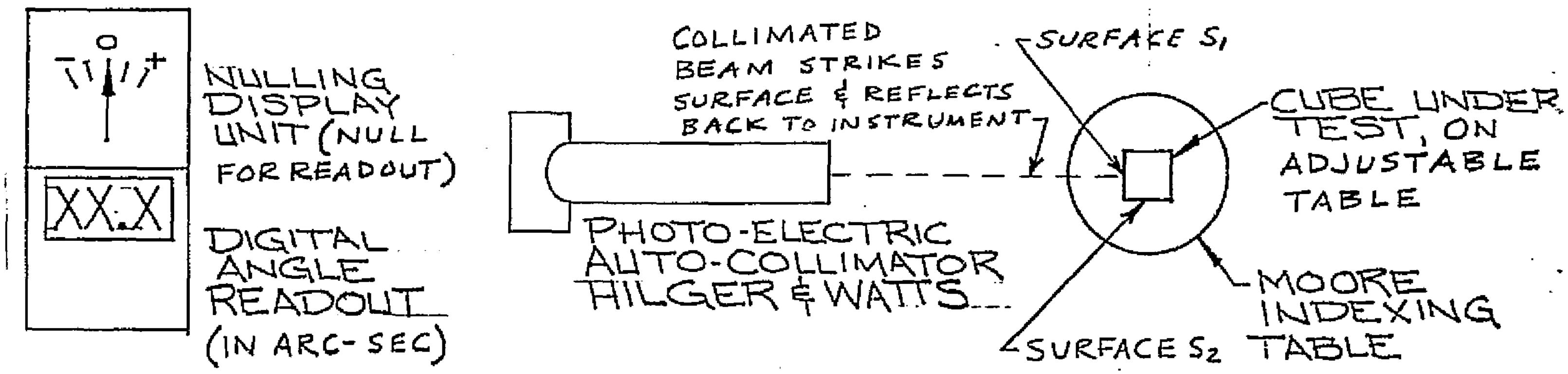
Upon completion of the generation of new interferograms for the LAGEOS retroreflectors at Itek, three of the retroreflectors were provided to Zygo for mechanical measurements of the dihedral angles by Zygo and, independently, by Moore Special Tool Company. Moore was selected because of their reputation in the optical industry as the source of precision indexing tables, used at the major optics fabricators (e.g., Zygo, Perkin-Elmer, Itek) and because of their past experience in the measurement of dihedral angles on master cubes. The remaining three retroreflectors were provided to Perkin-Elmer, at NASA/MSFC request, for similar mechanical measurements. The same three retroreflectors, as used at Zygo and Moore, were later supplied to Perkin-Elmer to provide an additional independent set of measurements on the same group of retroreflectors; the set originally supplied to Perkin-Elmer was selected for the retroreflector rework task.

The set-up for the mechanical measurements made at Zygo is shown in Figure 3-3. A Hilger & Watts Photo-Electric Auto-Collimator is utilized to generate a collimated light-beam and to measure to relative angle of the return beam from a reflective target. The reflective target, in this application, is the back face of a master cube, or a test cube, mounted on a Moore Precision Indexing Table. Initial set-up alignment utilizes a master cube having a known dihedral angle of 90^{o} + 0.2 arc sec. The cube mount alignment is adjustable and is set-up to give a zero digital readout when the light is reflected from one face (S_1) and a 0.2 arc sec digital readout after the Moore Indexing Table has been rotated 90^{o} and the light is then reflected from the second face (S_2). When a test cube is installed on the Moore Indexing Table, the difference between the digital readings from each face (S_1 and S_2) is the dihedral angle difference from a perfect 90^{o} (within the tolerance of the measurement set-up, about 0.2 arc sec).

The raw measurement data, for retroreflectors S/N 1, 2 and 4, is included in Appendix A,of this report, for both the Zygo and Moore Special Tool Company measurements. These results are summarized in Table 3-6. The measurements subsequently made by Perkin-Elmer are also included in Table 3-6; the individual angle measurements are not intended to correspond. In addition, measurements made at Zygo,prior to initial delivery of the retroreflectors on the basic program, are also included in Table 3-6. The wide variation between mechanical measurements can be

FIGURE 3-3

MECHANICAL MEASUREMENT SET-UP AT ZYGO



	Set-Up		Test	
Test Cube	Master Cube		LAGEOS Retroreflector	
Dihedral Angle	Known Value		To Be Measured	
	Surface	Digital Readout	Surface	Digital Readout
Moore Table as Shown	S_1	00.0	S_1	00.0
Moore Table Rotated 90°	S_2	00.2	S_2	Dihedral Angle - 90°

TABLE 3-6

DIHEDRAL ANGLE MEASUREMENTS

Retroreflector S/N	Moore (Arc Sec)*	Zygo (Arc Sec)* Operator #1	Zygo (Arc Sec)* Operator #2	Perkin-Elmer (Arc Sec)	Original Zygo (Arc Sec)
1	2.14 $\pm$ 0.02	2.10 $\pm$ 0.02	2.05 $\pm$ 0.03	1.7	2.00
	2.00 $\pm$ 0.07	1.67 $\pm$ 0.06	1.89 $\pm$ 0.07	1.7	1.24
	1.72 $\pm$ 0.09	1.55 $\pm$ 0.05	1.75 $\pm$ 0.03	1.7	0.92
2	1.68 $\pm$ 0.04	1.33 $\pm$ 0.02	1.63 $\pm$ 0.05	1.35	1.54
	1.84 $\pm$ 0.02	1.38 $\pm$ 0.06	1.81 $\pm$ 0.05	1.55	2.05
	1.76 $\pm$ 0.05	1.38 $\pm$ 0.03	1.76 $\pm$ 0.04	1.4	1.83
4	1.82 $\pm$ 0.02	1.68 $\pm$ 0.05	1.46 $\pm$ 0.03	1.65	2.00
	1.80 $\pm$ 0.03	1.24 $\pm$ 0.02	1.30 $\pm$ 0.05	1.5	1.57
	1.80 $\pm$ 0.06	1.23 $\pm$ 0.02	1.41 $\pm$ 0.02	1.5	1.60

* The average angles and standard deviations above are based on five (5) measurements of each retroreflector.

seen by an examination of this data. These results tend to support the use of interferogram data to determine dihedral angles.

Mechanical measurements by Zygo and Moore are compared with dihedral angles calculated from interferometric data by Itek in Table 3-2. The average dihedral angle from Moore measurements is about 1.84 arc sec, based on measurements of three retroreflectors, which corresponds closely with the Itek analysis results for these same retroreflectors of 1.82 arc sec. Close correspondence is not obtained for the Zygo measurements, which result in an average dihedral angle of 1.60 arc. sec.

4.0 INTIAL OPTICAL PERFORMANCE ANALYSIS

Far-field diffraction pattern performance predictions were generated, by Itek, for various retroreflector dihedral angles to evaluate the effect of this parameter on LAGEOS performance. In addition, performance predictions were generated, by Itek, for the original LAGEOS test retro-reflectors, based on their measured interferometric characteristics. The intent of this effort was to provide additional data for the correlation of theoretical and experimental retroreflector performance, to permit the preliminary selection of a more optimum nominal dihedral angle and to provide the basis for the consideration of a change in dihedral angle tolerance. These initial results were used to select the dihedral angles for the LAGEOS test retroreflector rework to be accomplished in Task 3.0 (Section 5.0). Correlation of the Itek and SAO analytical models, to correct previously-observed far-field intensity differences, was also inlcuded in this effort.

4.1 Input Data

Optical performance predictions were generated for retroreflectors having "nominal" (i.e. equal) dihedral angles of 90° + 0.9, + 1.25 and + 1.75 arc seconds. Data was already available, from the basic study, for dihedral angles of + 1.5 and + 2.1 arc seconds. As before, the laser wavelength of 6328 Å and a linearly-polarized beam (parallel to a real edge of the retroreflector) were the basis for the predictions.

Predictions were also obtained for retroreflectors having off-nominal dihedral angles, where the three dihedral angles of the retroreflector were assumed to be 90° + 0.4, + 0.9 and + 1.3 arc seconds, respectively. Data had been generated previously for two other sets of dihedral angles: 90° + 1.0, + 1.5 and + 2.0 arc seconds and 90° + 1.6, + 2.1 and +2.6 arc seconds. These input dihedral angles were utilized in the Itek "tolerance study", as it is identified and described in Appendix E of this report.

The basis for the generation of optical performance predictions for the LAGEOS test retroreflectors was the measured wavefront data for each retroreflector, obtained from interferograms generated by Itek, as described previously in Section 3.0.

4.2 Performance Analysis Method

The detailed modeling, assumptions and analytical processes used by Itek to predict far-field diffraction performance were the same as used in the basic study. These are described in detail in Appendix Q of the basic study Final Report, BSR 4159. The analytical approach used to incorporate the LAGEOS test retroreflector interferometric data in the analysis is described in Appendix E of this report.

4.3 Tolerance Study Performance Predictions

Detailed far-field pattern energy distribution predictions, in the form of computer print-out data, are given in Appendix E. The energy in the LAGEOS annulus of 13.2 - 16.9 arc sec diameters, obtained from this data, is plotted in Figure 4-1 for the dihedral angles evaluated in the basic study and in this initial analysis effort. Predictions were later extended, in the analysis effort described in Section 6.0, for dihedral angles down to a "perfect" 90^o retroreflector and these are reflected in the plots of Figure 4-1. Curves are shown for both the nominal dihedral angle retroreflectors (cubes) and the off-nominal dihedral angle retroreflectors. Based on the data for the perfect retroreflectors, the optimum dihedral angle appears to be at $90^o + 1.35$ arc sec. If the off-nominal condition is considered to represent a more realistic dihedral angle set, the optimum dihedral angle appears to be at about $90^o + 1.25$ arc sec.

The centroid of the energy in the far-field pattern was also obtained from the predicted intensity data given in Appendix E. For the purposes of this analysis, the centroid was assumed to be at the diameter of maximum rate-of-change of intensity. Comparison of the resulting energy centroid data provides an understanding of the effect of dihedral angle on energy distribution in the far-field pattern. Predicted centroid diameter, as a function of average dihedral angle, is shown in Figure 4-2 for both nominal and off-nominal retroreflectors. This data does confirm that the optimum dihedral angle for the off-nominal retroreflectors occurs at a lower dihedral angle than for a nominal retroreflector.

The energy centroids predicted from only geometric considerations are also plotted, as a function of dihedral angle. The data for the nominal and off-nominal retroreflectors includes the effects of polarization and diffraction which were expected to be the reasons for the difference in centroid location from the geometric data. At a large dihedral angle (e.g. $90^o + 5.0$ arc seconds), the centroid from geometric considerations matched the predicted centroid from the analysis which included polarization and diffraction considerations (47.5 arc sec diameter); this confirmed the expected results. In addition, predictions were made without the polarization effects at the nominal dihedral angle cases and the results are also shown in Figure 4-2 (identified by $\boxed{\cdot}$). Since these results closely approximate the geometric data, it was concluded that the deviation of performance, from that predicted by simple geometric considerations, is primarily due to polarization effects and that diffraction effects are small.

4.4 LAGEOS Test Retroreflector Performance Predictions

The performance predictions generated for each of the original LAGEOS test retroreflectors are given, in detail computer print-outs of intensity

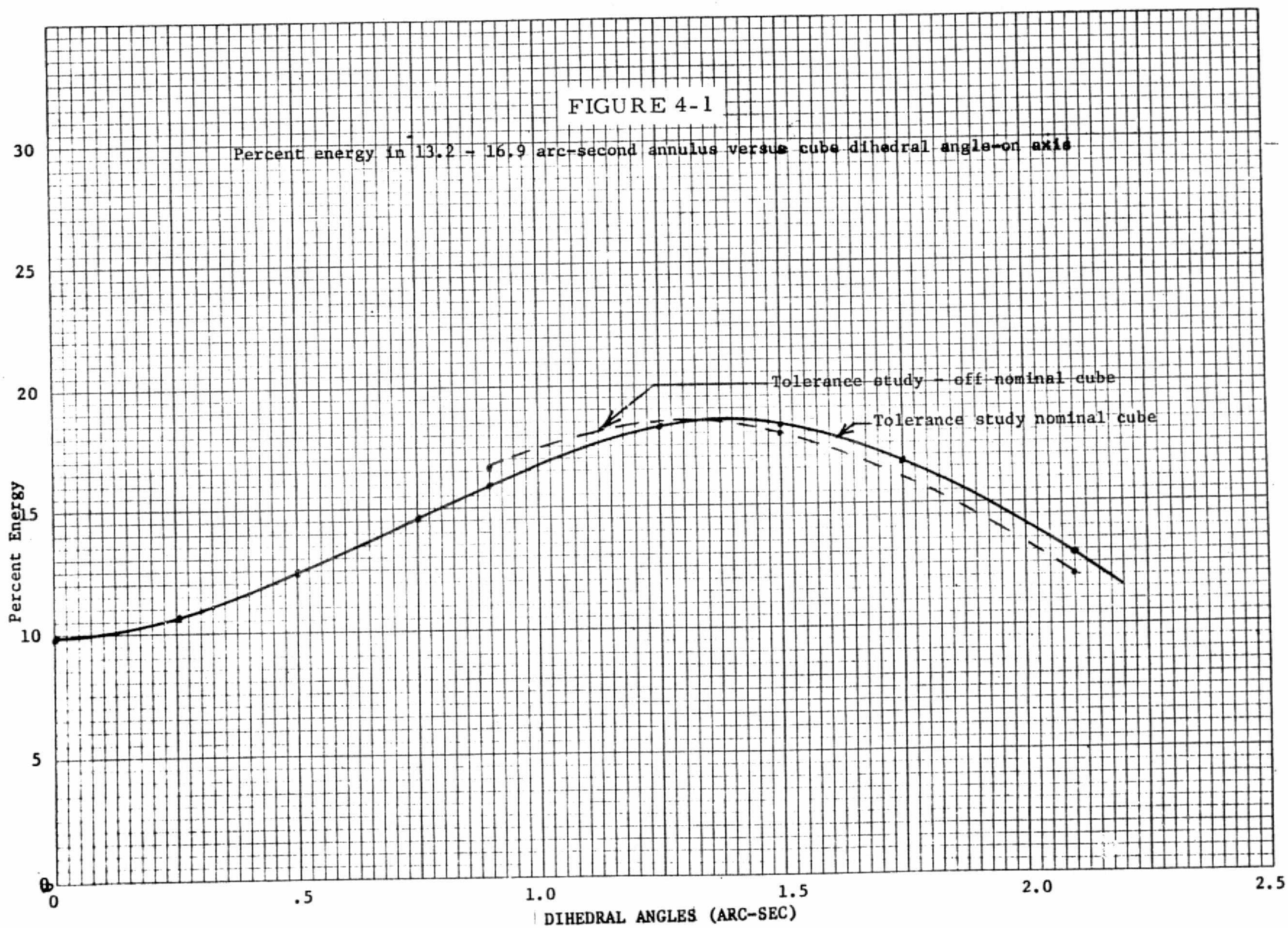


FIGURE 4-1

Percent energy in 13.2 - 16.9 arc-second annulus versus cube dihedral angle-on axis

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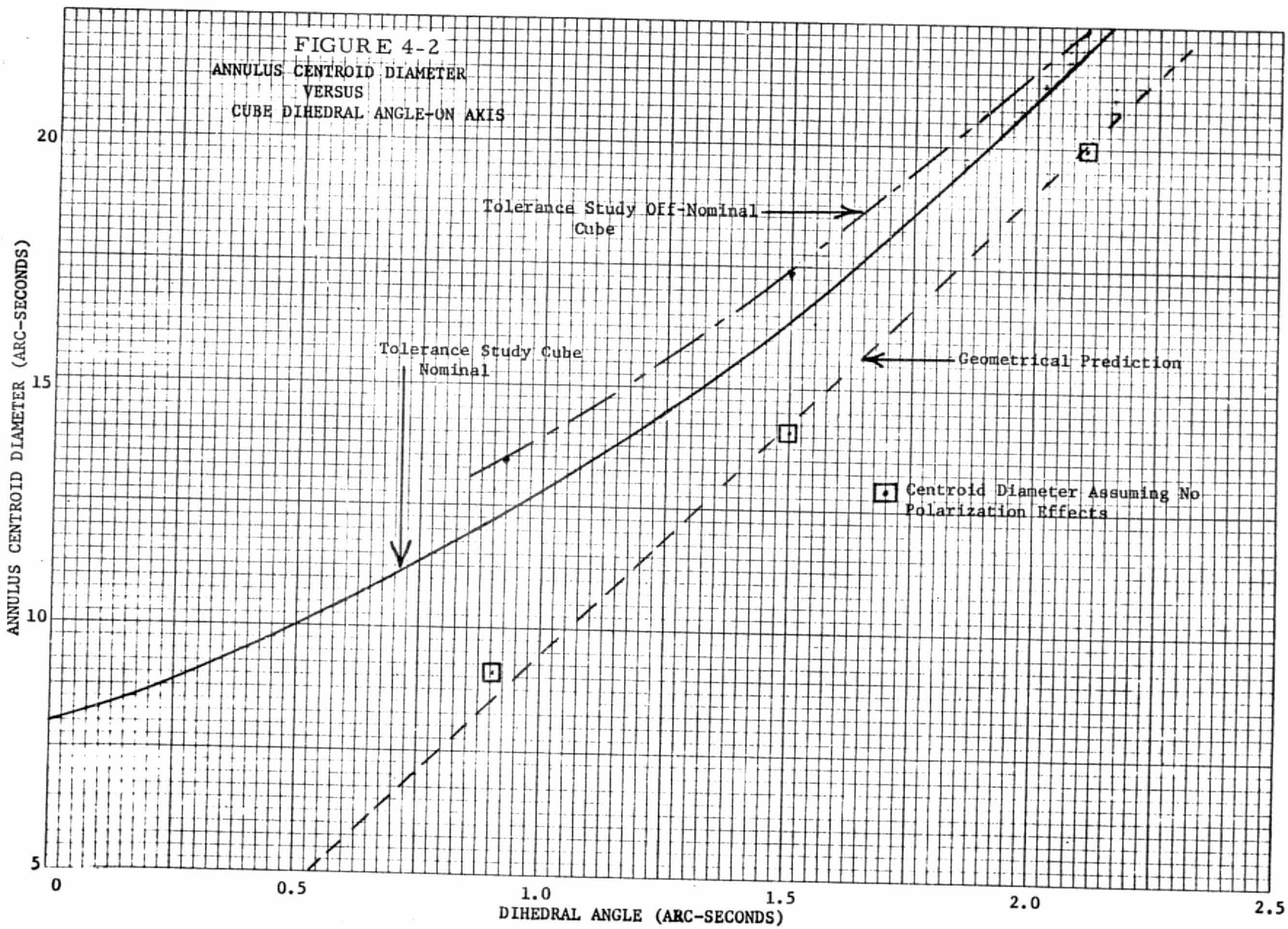


FIGURE 4-2
ANNULUS CENTROID DIAMETER
VERSUS
CUBE DIHEDRAL ANGLE-ON AXIS

distribution, in Appendix E. The predicted energy, in the LAGEOS annulus of 13.2 - 16.9 arc seconds diameters, is tabulated in Table 4-1 and plotted in Figure 4-3 for each retroreflector, in terms of the average dihedral angle predicted by Itek from interferogram analysis for each respective retroreflector. For comparison purposes, energy measurements in the LAGEOS annulus, obtained in the Bendix optical tests during the basic study, are also plotted for each retroreflector at the Itek-derived average dihedral angle. In each case, the predicted performance is greater than the measured performance. The predicted performance for retroreflector S/N 3 appears to be too low; however, re-evaluation of the analysis confirmed the plotted performance data. Results of the tolerance study are also included, to show the comparison with theoretical performance.

The predicted energy centroid was also obtained from the detail intensity distribution data, in the same manner as described in Section 4.3. This data is tabulated in Table 4-1 and plotted in Figure 4-4, as a function of the average Itek-derived dihedral angle. Measurements made from photographs of the far-field diffraction pattern, during the basic study, to estimate the energy centroid location are also plotted in Figure 4-4, for comparison purposes. The measured data are based on estimates of the location of the "bright area" centroid and conversion of this linear measurement, in millimeters, by the Far-Field Diffraction Instrument (FFDI) scale-factor, to obtain the centroid diameter in arc seconds. These data, originally given in the basic Final Report (BSR-4159), are also plotted in Figure 4-4. It should be noted that the "measured" energy centroid for the dihedral angles of the original LAGEOS test retroreflector, is, in general, larger in diameter than that determined from far-field pattern analytical predictions. This result is compatible with the results described earlier for the energy in the LAGEOS annulus.

Evaluation of all of the predicted and test data for the LAGEOS test retroreflectors indicated that, while the data agrees with the trend shown by the nominal and off-nominal perfect retroreflector predictions, it is necessary to obtain data for actual retroreflectors having low values of dihedral angle, to establish the optimum dihedral angle. This confirmed the validity of Tasks 3, 4 and 5, as originally planned. The results also provide the basis for selection of the dihedral angles for the rework retroreflectors; dihedral angles of 90° + .75, + 1.0 and + 1.25 arc sec were selected to extend the range of empirical data.

4.5 Itek/SAO Math Model Correlation

At the completion of the basic study, some differences identified during the program still existed between the Itek and SAO far-field intensity predictions. Modifications were subsequently made in the Itek analytical model, as a result of telecon discussions between the Itek and SAO cognizant personnel. After

TABLE 4-1

FAR-FIELD CHARACTERISTICS OF LAGEOS
RETROREFLECTOR - ON-AXIS

Retroreflector S/N	Percent Energy in 13.2 - 16.9 Arc-Sec Annulus		Centroid Diameter (Arc Sec)	
	Itek Interferogram	Bendix Measurement	Itek Interferogram	Bendix Measurement
1	14.0	8.9	18.6	22.0
2	13.6	8.9	20.2	19.8
3	14.7	12.4	16.4	17.6
4	14.6	9.0	18.6	20.6
5	11.7	6.7	21.9	23.5
6	17.4	12.0	16.6	18.4
Average	14.3	9.7	18.3	20.3

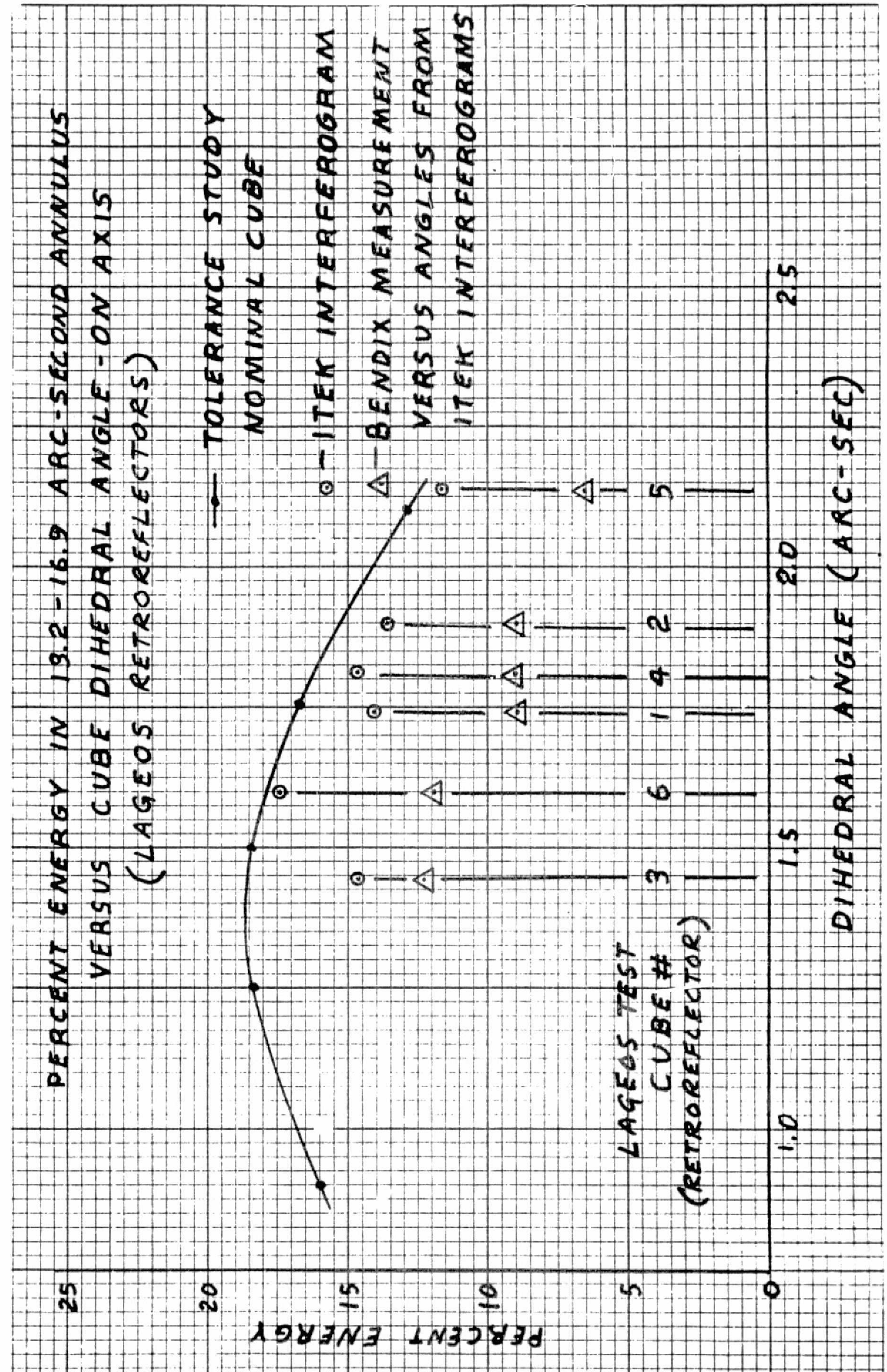
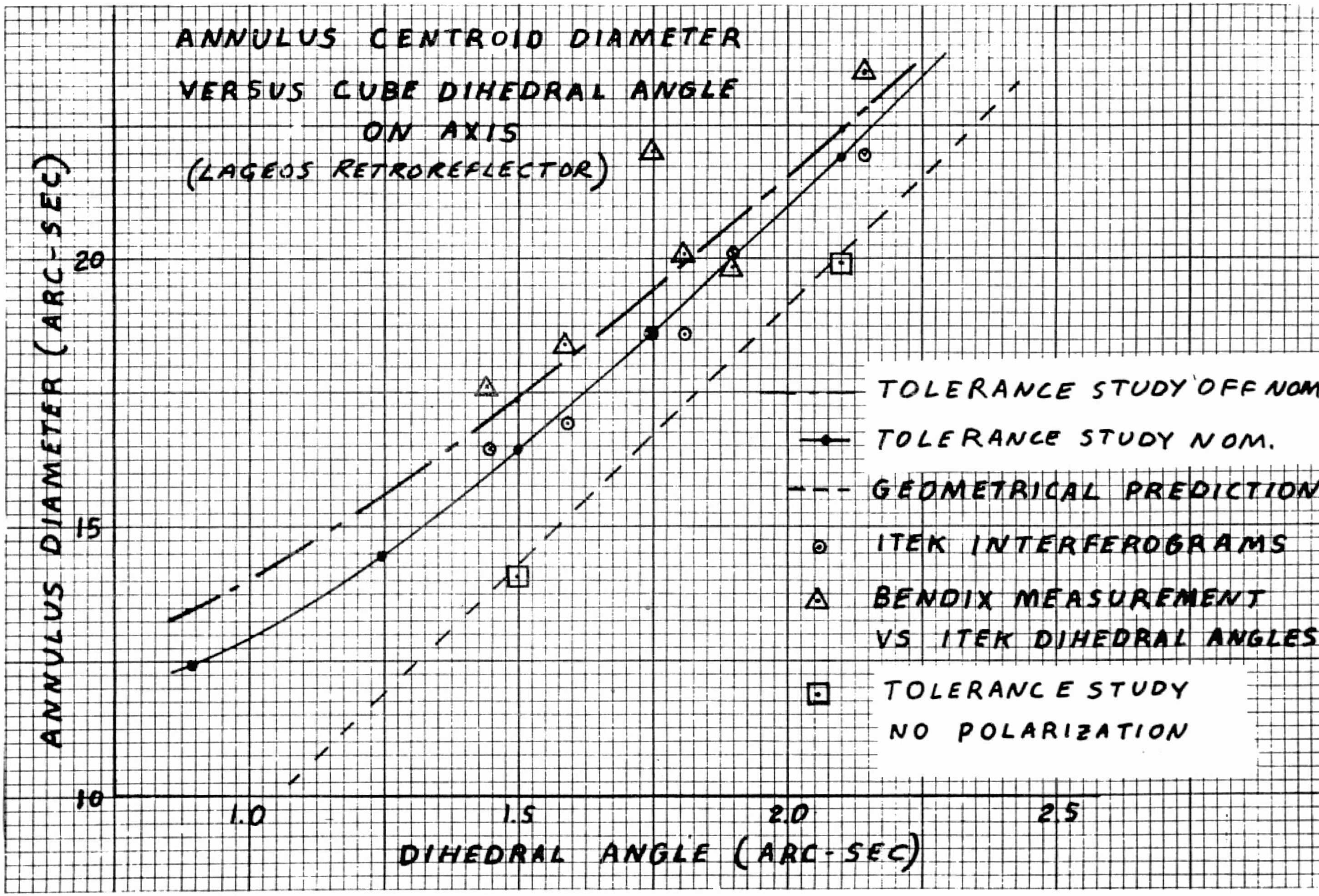

PERCENT ENERGY IN 13.2 - 16.9 ARC-SECOND ANNULUS
VERSUS CUBE DIHEDRAL ANGLE - ON AXIS
(LAGEOS RETROREFLECTORS)
TOLERANCE STUDY
NOMINAL CUBE
ITEK INTERFEROGRAM
BENDIX MEASUREMENT
VERSUS ANGLES FROM
ITEK INTERFEROGRAMS
LAGEOS TEST
CUBE #
(RETROREFLECTOR)
3
6
1
4
2
5
PERCENT ENERGY
0
5
10
15
20
25
1.0
1.5
2.0
2.5
DIHEDRAL ANGLE (ARC-SEC)

FIGURE 4-3

FIGURE 4-4



ANNULUS CENTROID DIAMETER
VERSUS CUBE DIHEDRAL ANGLE
ON AXIS
(LAGEOS RETROREFLECTOR)
ANNULUS DIAMETER (ARC-SEC)
20
15
10
1.0
1.5
2.0
2.5
DIHEDRAL ANGLE (ARC-SEC)
TOLERANCE STUDY OFF NOM.
TOLERANCE STUDY NOM.
GEOMETRICAL PREDICTION
ITEK INTERFEROGRAMS
BENDIX MEASUREMENT
VS ITEK DIHEDRAL ANGLES
TOLERANCE STUDY
NO POLARIZATION

agreement had been obtained between SAO and Itek predictions, the effect on energy predictions in the LAGEOS annulus was a change in the results of less than 0.1%.

5.0 LAGEOS TEST RETROREFLECTOR REWORK

Based on the conclusions reached in the First Data Review Meeting (described in Section 4.4), LAGEOS test retroreflectors S/N 3, 5 and 6 were selected for rework at Zygo to new dihedral angle requirements. S/N 1, 2 and 4 retroreflectors were provided to Perkin-Elmer to perform an additional independent set of dihedral angle measurements; these same retroreflectors were subsequently used at Bendix in the optical performance tests, to provide a data baseline for comparison with earlier test results.

The rework effort was intended to produce three LAGEOS test retroreflectors, having average dihedral angles of 90^{o} + 0.75, 1.0 + 1.25 arc sec, respectively. Soon after the start of the rework effort, retroreflector S/N 6 was damaged, beyond repair as an optical test unit. A GFE Apollo (ALSEP) flight retroreflector (i.e., fabricated from Supersil I Special, the same material as that specified for LAGEOS) was substituted and reworked, with NASA concurrence. The damaged retroreflector was repaired for potential use as a dummy unit, by stoning the chipped area and by polishing the back surfaces only sufficient to provide a finished appearance.

Mechanical measurements were made, by Zygo, of the dihedral angles after rework. The raw measurement data is included in Appendix B of this report. The measurement technique used by Zygo was the same as that used in the earlier dihedral angle measurement effort and described in Section 3.0.

The results are summarized in Table 5-1, where the average dihedral angles are also shown. According to these measurements, the desired dihedral angles are closely achieved, on an average basis.

Interferograms were also generated at Zygo for each of the reworked retroreflectors. The retroreflectors were left uncoated for the interferograms, of which three were made for each retroreflector. Each interferogram is oriented with the fringes rotated at 120^{o} from the other two interferograms and with the fringes perpendicular to a real edge. A complete set of interferograms was provided to Itek for the final optical analysis effort. These are shown in Appendix E. One interferogram for each reworked retroreflector is shown in Figure 5-1.

Table 5-1

DIHEDRAL ANGLE MEASUREMENTS

REWORKED RETROREFLECTORS

RETROREFLECTOR S/N		DIHEDRAL ANGLES* (ARC SEC)	AVG. DIHEDRAL ANGLE (ARC SEC)
1 RW	1-2	0.97	0.98 AVG.
	2-3	1.10	
	3-1	0.86	
2 RW	1-2	1.37	1.29 AVG.
	2-3	1.26	
	3-1	1.24	
3 RW	1-2	0.72	0.79 AVG.
	2-3	0.84	
	3-1	0.82	

*BASED ON AVERAGE OF FIVE (5) MECHANICAL MEASUREMENTS

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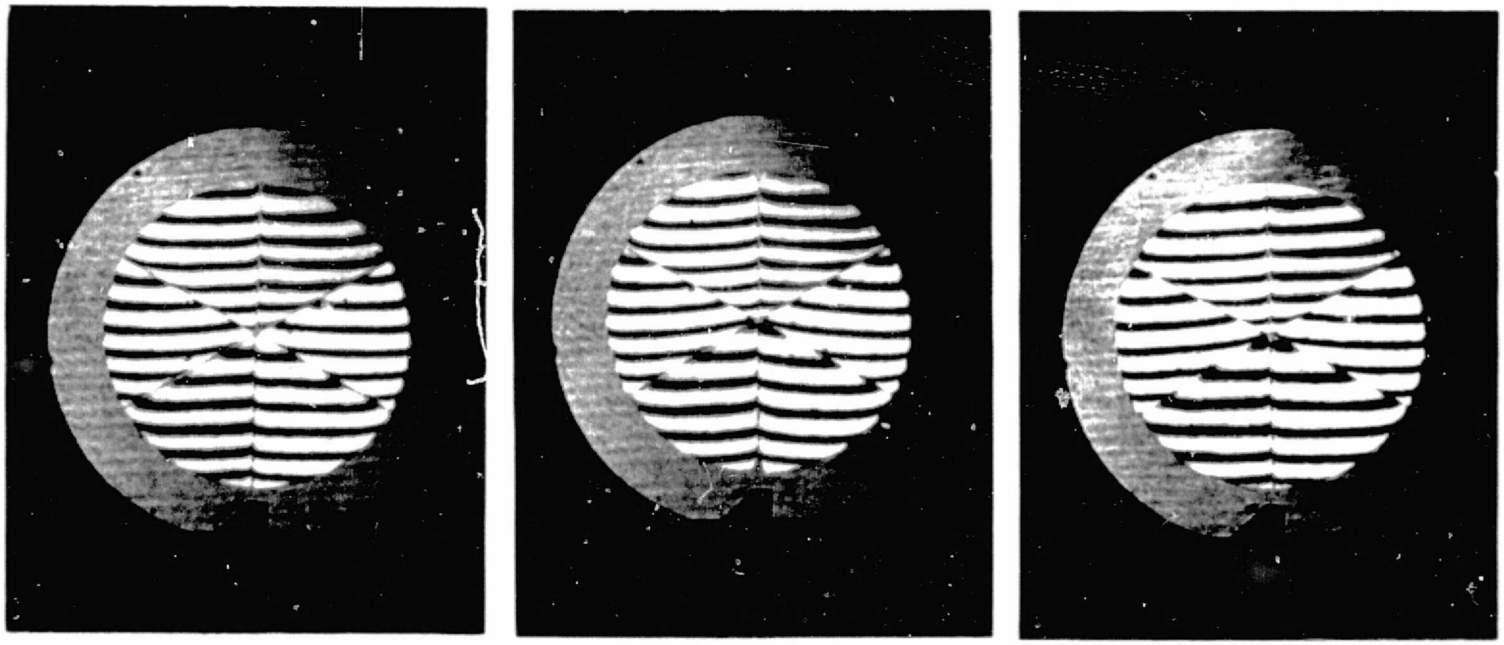
INTERFEROGRAMS OF REWORKED CUBES



#1 RW | #2 RW | #3 RW

FIGURE 5-1

6.0 FINAL OPTICAL PERFORMANCE ANALYSIS

The intent of this effort was to analyze the interferograms for the reworked retroreflector and to generate predicted optical performance for each reworked retroreflector. This additional data was required to confirm the conclusions reached previously in the First Data Review Meeting.

6.1 Input Data

The new inputs, for this analysis, are the three interferograms for each reworked retroreflector provided to Itek for the analysis. These interferograms are shown in Appendix E. In generating the interferograms, the input beam was linearly-polarized, with the direction parallel to a different real edge in each interferogram.

6.2 Dihedral Angle Predictions

The dihedral angles were determined for each reworked retroreflector, using the analysis technique previously summarized in Section 4, and described in detail in Appendix E. These results are listed in Table 6-1. A difference of about 0.5 arc sec was obtained between the Zygo data (Table 5-1) and the Itek data (Table 6-1). No changes in measurement or analysis techniques could be identified at Zygo or Itek to establish the reasons for this difference.

6.3 Reworked Retroreflector Performance Predictions

The wavefront data was calculated for each reworked retroreflector and used, in the same manner as summarized previously in Section 4,to generate predicted far-field diffraction pattern data. The analytical technique employed is described in detail and output data is shown in Appendix E.

The predicted energy intensity in the LAGEOS annulus (13.2 - 16.9 arc sec. diameters), obtained from this data, is shown in Table 6.2. These results are also plotted, with the previously obtained results for the original LAGEOS test retroreflectors, in Figure 6-1. The dihedral angles,used for the plot of reworked retroreflector data, are those resulting from the Itek analysis of the interferograms (Section 6.2). The resulting data is close to the predicted values for perfect-nominal retroreflectors, except for the retroreflector S/N 2 RW data. This correspondence between data is to be expected,since the intensity data and dihedral angles are derived from the same source (i.e. the interferograms for the reworked retroreflectors).

The predicted energy centroid diameters were also obtained from the far-field predictions, by the definition of centroid location previously

TABLE 6-1

INTERFEROMETRIC MEASUREMENT OF DIHEDRAL ANGLES

ON REWORKED RETROREFLECTORS (ARC-SEC)

	INTERFEROGRAM				
Reworked Retroreflector S/N	1	2	3	Average	A
1 RW	.73 .30 .45	.79 .38 .33	.83 .28 .30	.78 .32 .36	.
2 RW	.67 .89 .77	.58 .91 .73	.91 .79 .59	.72 .86 .70	.
3 RW	.28 .17 .40	.24 .30 .16	.25 .26 .30	.26 .24 .29	.

Based on Interferogram Produced by Zygo and Analyzed by Itek

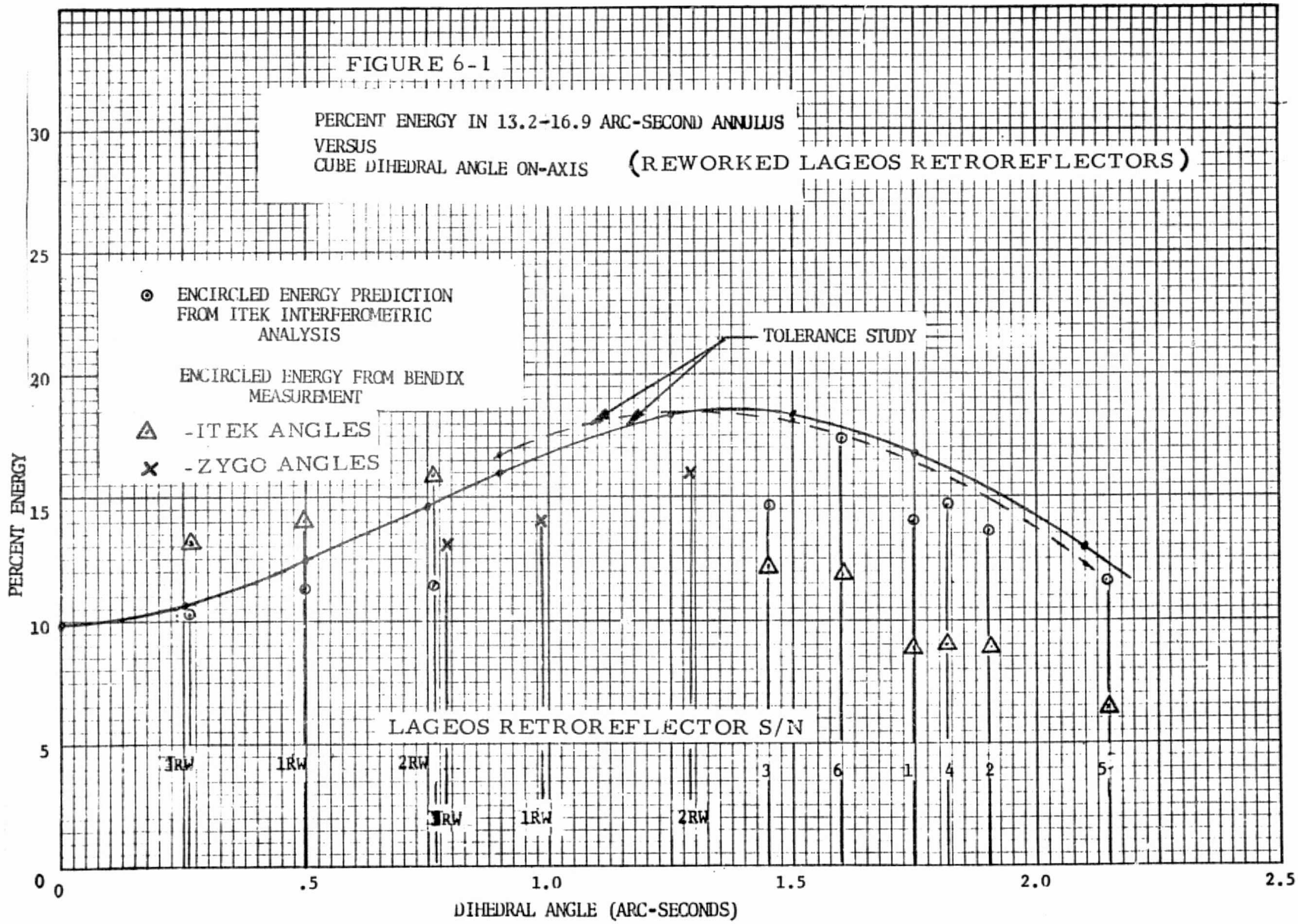
TABLE 6-2

FAR-FIELD CHARACTERISTICS OF
REWORKED RETROREFLECTOR (ON-AXIS)

Reworked Retroreflector S/N	Percent Energy 13.2 - 16.9 Arc Sec Annulus		Centroid Diameter (Arc-Sec)	
	Itek Interferogram	Bendix Measurement	Itek Interferogram	Bendix Measured
1 RW	11.35	14.0	9.4	13.2
2 RW	11.5	16.0	10.5	14.7
3 RW	10.4	13.0	7.9	12.5

Based on Interferogram Produced by Zygo and Analyzed by Itek

described in Section 4. These results are also listed in Table 6-2. The energy centroids are plotted in Figure 6-2, with the results previously predicted for the original LAGEOS test retroreflectors. Reasonable agreement with the predicted values for the perfect retroreflector is expected, and does result, since the data is based on intensity data and dihedral angles derived from the same source (i. e. the interferograms for the reworked retroreflectors).



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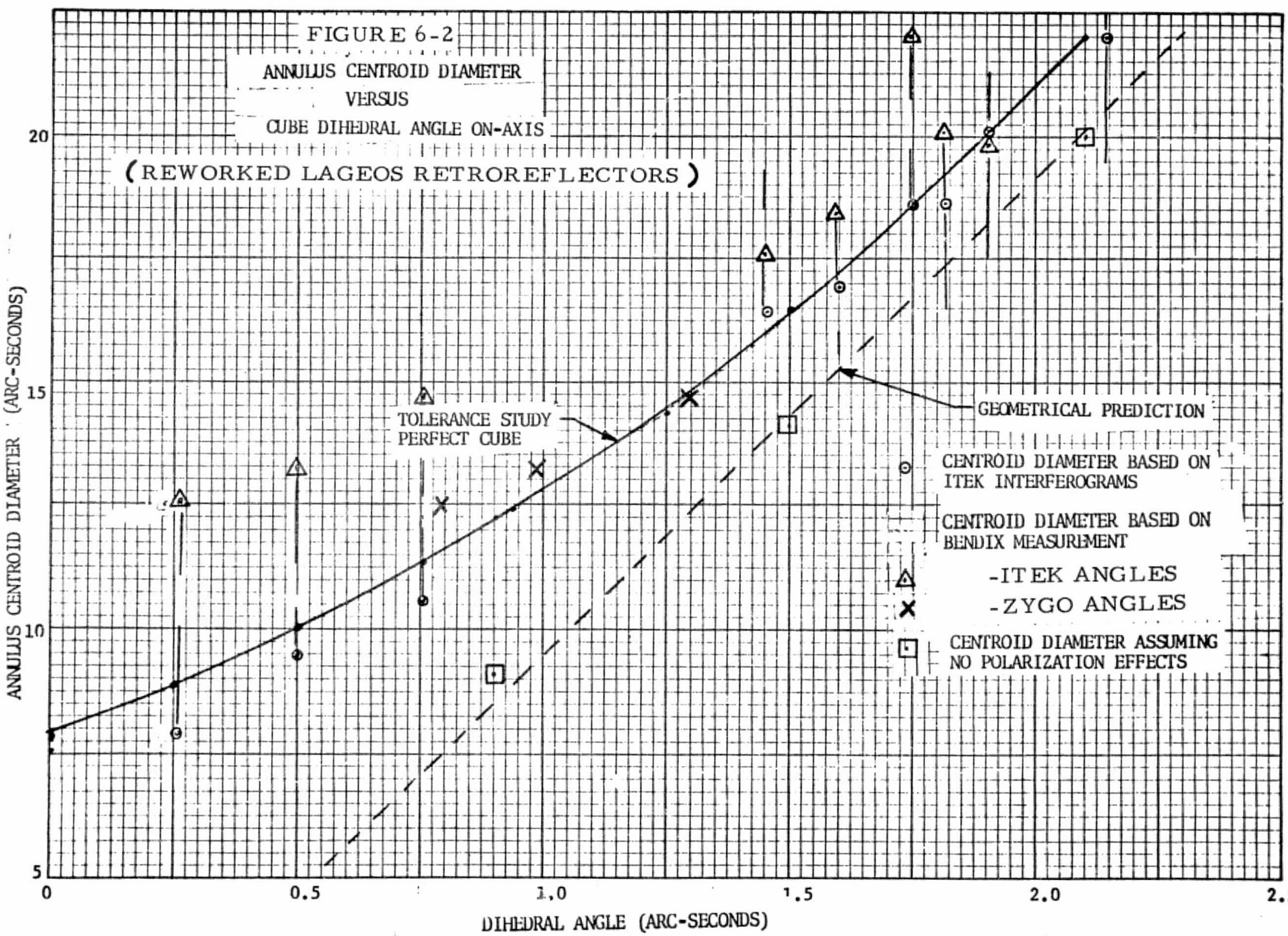

FIGURE 6-2
ANNULUS CENTROID DIAMETER
VERSUS
CUBE DIHEDRAL ANGLE ON-AXIS
(REWORKED LAGEOS RETROREFLECTORS)

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7.0 OPTICAL PERFORMANCE TESTS

To verify the optical performance predicted for lower dihedral angles (the objective of this effort), optical tests were made with the LAGEOS test retroreflectors after rework to lower average dihedral angles. Optical tests were also made, with the remaining three original LAGEOS test retroreflectors, to verify the test set-up and instrumentation.

7.1 Test Article Description

The test article,as used in these tests, is essentially the same as that used in the basic study program tests. The exception is, the substitution of the reworked retroreflectors for those previously installed in the test article.

Reworked retroreflectors, S/N 1RW, 2RW and 3RW, were installed in test article panel cavities, A, B and C, respectively. The original retroreflectors, S/N 1, 4 and 2, were installed in cavities D, E and F, respectively, of the test article panel. The mounting hardware consisted of the LAGEOS flight design lower and upper KEL-F rings and aluminum retainer ring and were the same as used on the original tests. Three aluminum #2-56 screws (MS 35202-8) were used to fasten each retro-reflector/mount assembly, as in the flight design.

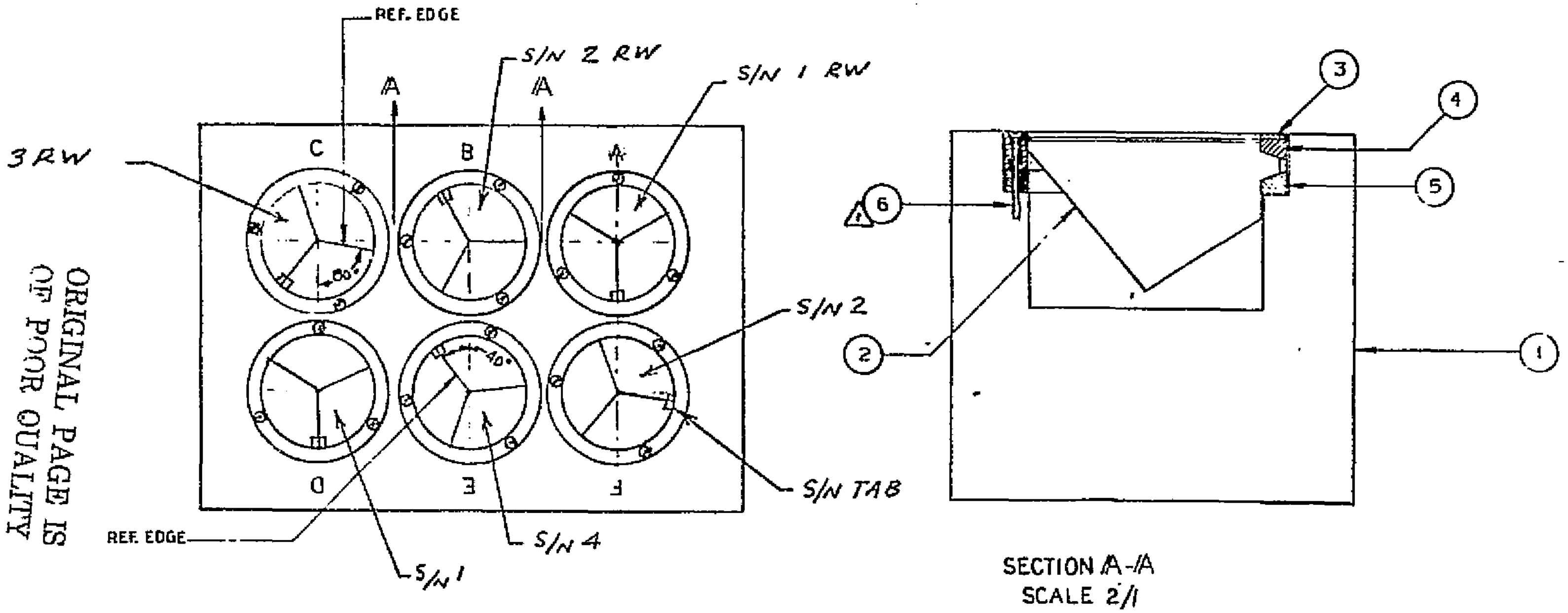
Only one problem was encountered in the assembly operation. The aluminum screw in the "one o-clock" position of the "C" cavity jammed during assembly. The screw head was broken, in trying to remove the screw, but the remainder of the screw was left in the threaded hole during the tests. The remaining two screws were sufficient to hold the rings and the retroreflector in place during the optical tests, with no effect on optical characteristics. Also, structural integrity was not a major concern since no dynamic tests were to be run in this test effort. Post-test inspection, of that portion of the screw later removed from the panel and of the threaded hole in the panel, indicated severely damaged threads in both the hole and the screw. The problem was probably caused by a burr in the threaded hole or on the screw threads, which could have been generated during the screw installation operation. Because both the panel threads and the screws were well cleaned and degreased prior to test to minimize contamination of the retroreflectors, no residual lubricant could be expected to remain on either side of the threads,a condition which would tend to increase resistance to relative motion between the threads.

The test article assembly is defined in Figure 7-1 and is shown, installed in the test fixture, in Figure 7-2. The upper three cavities in the test article are those designated C, B, A, from left to right, and contain

FIGURE 7-1

NOTES:

1. TORQUE ITEM 6 TO $1.4^{+0}_{-.2}$ IN-LBS.
2. CLEAN, HANDLE AND ASSEMBLE IN ACCORDANCE WITH 2374465



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RETROREFLECTORS	
S/N	DESCRIPTION
1	9118-1001 (ORIGINAL)
2	9118-1001 (ORIGINAL)
1 RW	9118-1001 (REWORKED)
4	9118-1001 (ORIGINAL)
2 RW	9118-1001 (REWORKED)
3 RW	100-2664-001 (REWORKED)

QTY REQD	DESCRIPTION	CODE IDENT	PART OR SPECIFICATION NO.	ITEM
13	SCREW		MS 35202-8	6
6	LOWER RING		2374462	5
6	UPPER RING		2374461	4
6	RETAINER RING		2374463	3
6	RETRO		AS NOTED	2
1	PANEL		2374464	1

LIST OF MATERIALS

LAGEOS TEST ARTICLE
ASSEMBLY

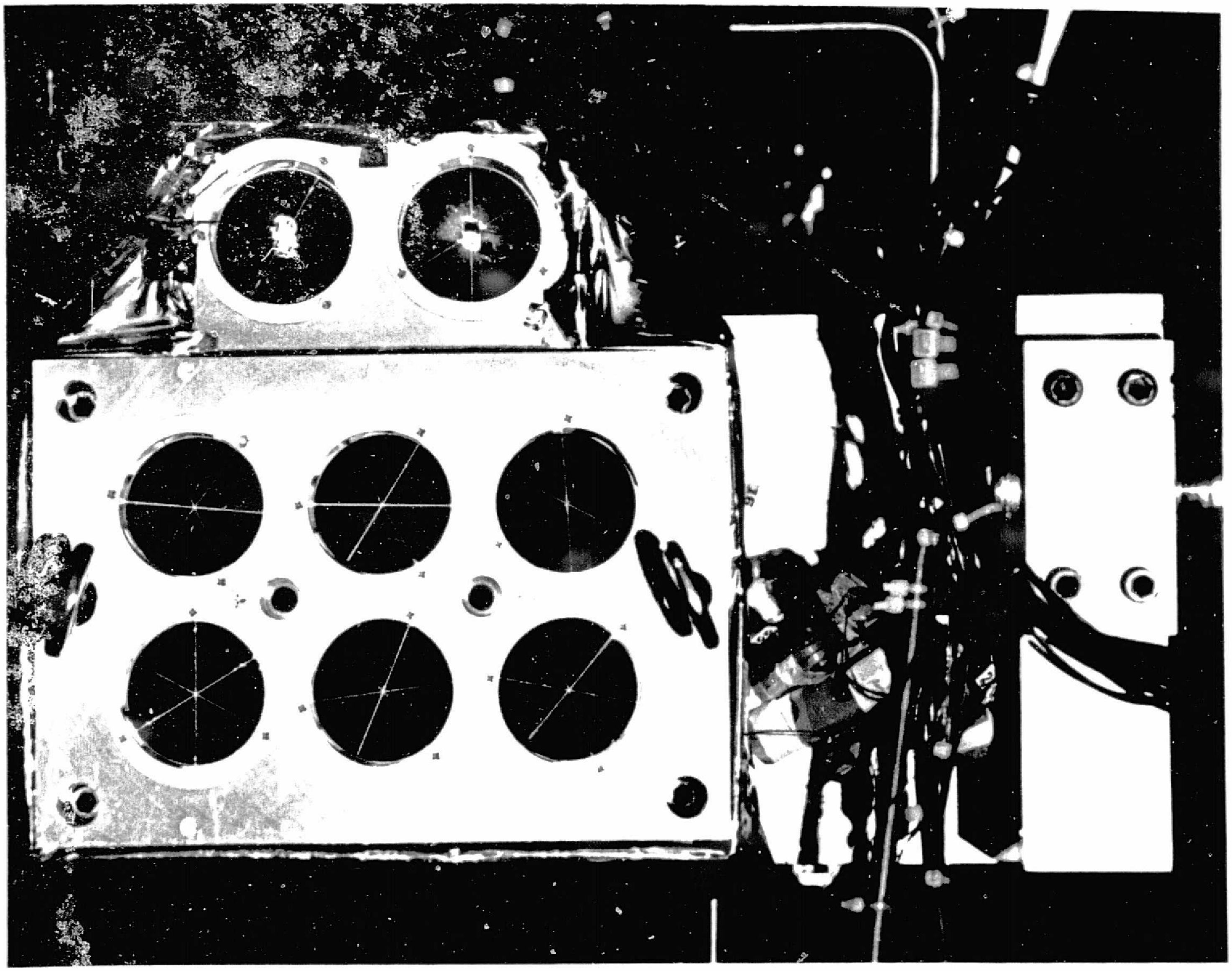


FIGURE 7-2
LAGEOS TEST ARTICLE

the reworked retroreflectors S/N 3RW, 2RW and 1RW, respectively.

7.2 Test Method

The test arrangement used for these tests was the same as used in the basic test program, except that simulation of the LAGEOS thermal environment was not required. The test article was mounted on the LAGEOS test fixture in the Bendix 4' x 8' thermal/vacuum chamber. The thermocouple fixture, installed on the test fixture as in the previous tests, was available to monitor test article temperatures. No earth-IR or solar simulation was required, nor was the cold wall required to be activated. All tests were performed at isothermal conditions and at ambient pressure and at vacuum. The test set-up is shown in Figure 7-3. The test article, installed in the test fixture and set-up in the vacuum chamber, is shown in Figure 7-4. The test fixture manipulator and the data acquisition system, used to record thermal data, are shown in Figure 7-5; the power panel shown was not used in these tests.

The basic optical performance measurement instrumentation was provided by the Far-Field Diffraction Instrument (FFDI). The laser beam, having a wavelength of 6328 Å, was provided by the FFDI and was directed at each test retroreflector through an optical-quality window in the end of the chamber. Through manipulation of the test fixture controls on the outside of the chamber, each retroreflector, of a three-retroreflector group, was aligned with the incident laser beam. All tests were made with the incident beam normal to the front face of each retroreflector. The beam is returned from the retroreflector, passes through the optical window and is received by the FFDI. The far-field pattern is then displayed and photographed and photometric measurements are made of the energy in a selected portion of the pattern (i.e., the energy in the LAGEOS annulus from 13.2 to 16.9 arc sec diameters and in the full field, within a 107.5 arc sec diameter, in this set-up). Measurements are also made for a calibration retroreflector, inserted between the FFDI and the optical window, before and after each series of tests. The FFDI is shown in Figure 7-6.

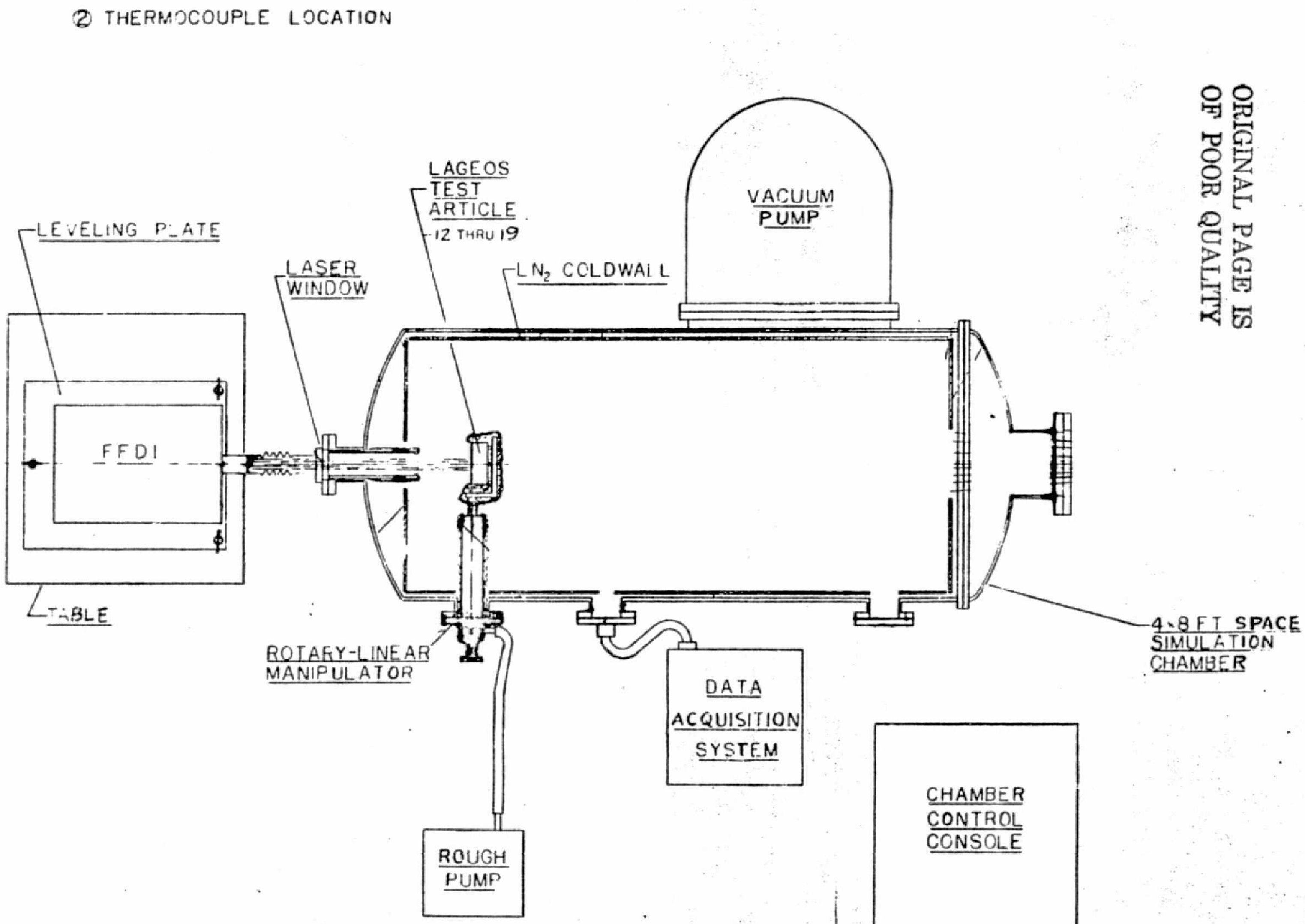
Data was taken for each retroreflector (both reworked and original) at isothermal-ambient, at isothermal-vacuum and, finally, at isothermal-ambient to result in two sets of data for each retroreflector at each condition.

7.3 Test Results

The "raw data" test results are shown in the as-run test procedure, Appendix C. The FFDI photographic test results are shown in Appendix D.

The far-field intensity data was reduced to produce the results summarized in Table 7-1. Both isothermal-ambient pressure and isothermal-vacuum data is

FIGURE 7-3



LAGEOS TEST SETUP - THERMAL-VACUUM

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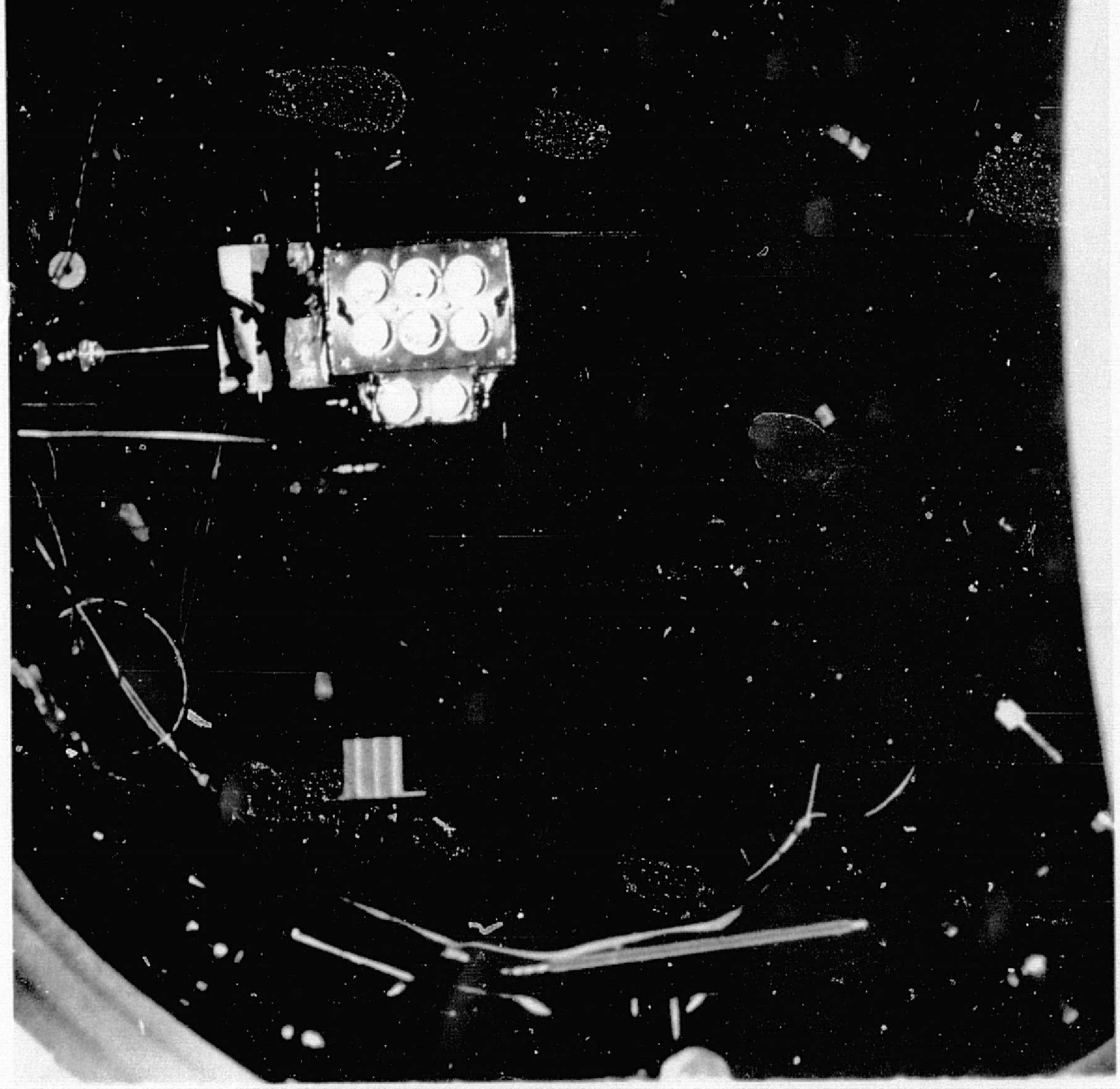

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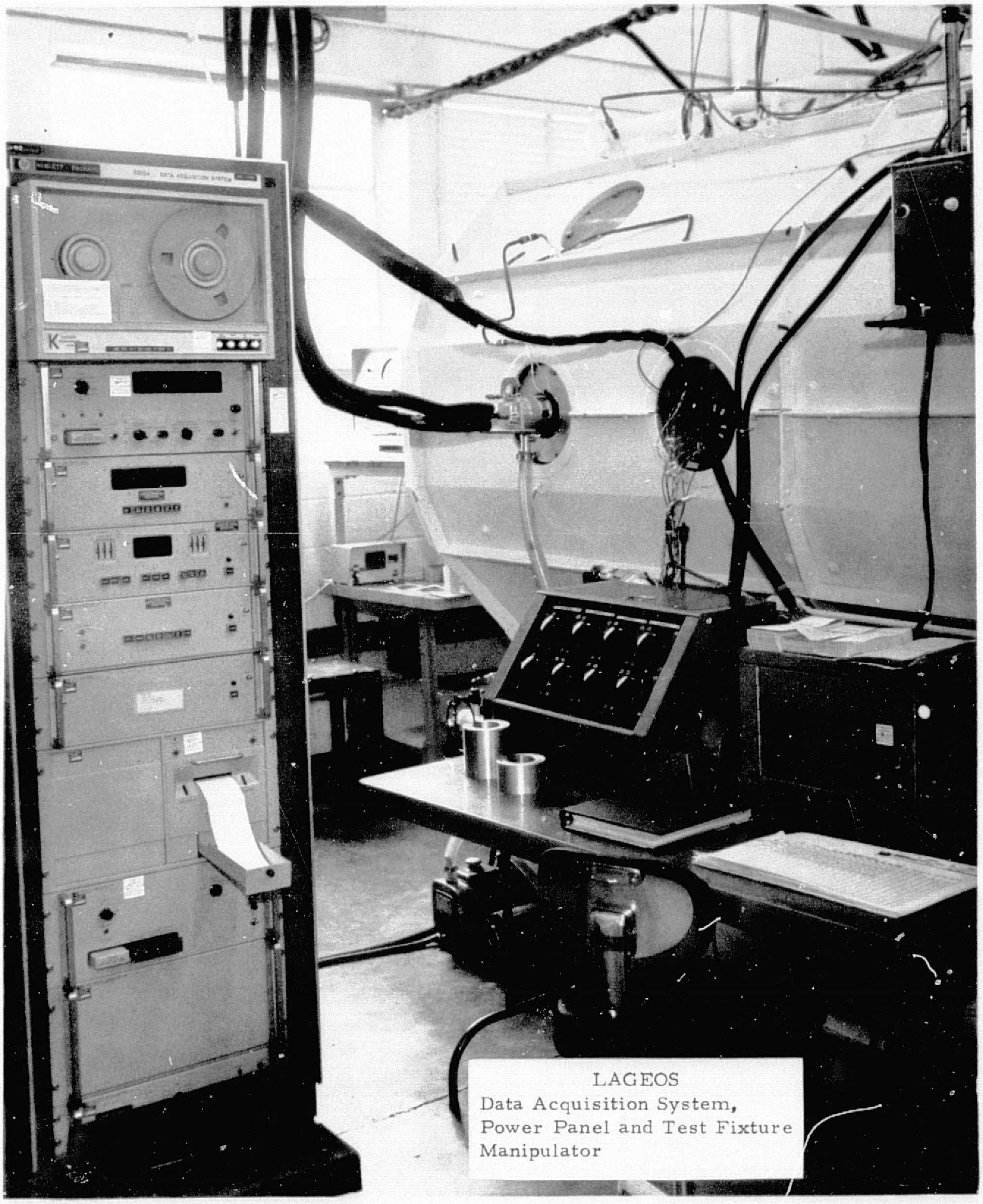
FIGURE 7-4
LAGEOS TEST ARTICLE
INSTALLED IN THERMAL/VACUUM CHAMBER



LAGEOS
Data Acquisition System,
Power Panel and Test Fixture
Manipulator

FIGURE 7-5

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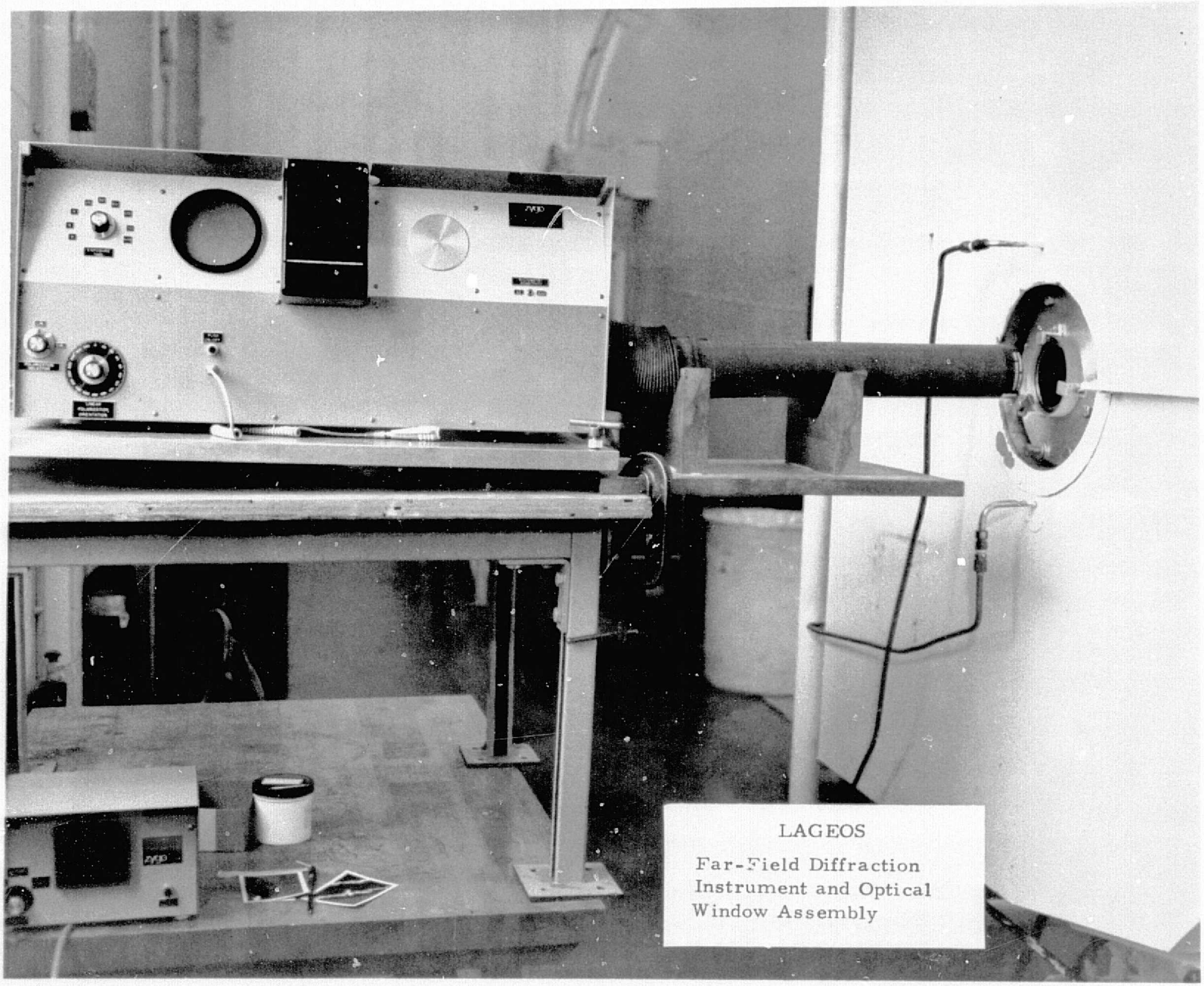

LAGEOS

Far-Field Diffraction Instrument and Optical Window Assembly

FIGURE 7-6

TABLE 7-1

SUMMARY - OPTICAL TEST RESULTS

RETROREFLECTOR S/N	AVG. DIHEDRAL ANGLE (ARC SEC)	FAR-FIELD INTENSITY ANNULAR-TO-FULL FIELD RATIO ISOTHERMAL-VACUUM	ISOTHERMAL-AMBIEN
1 RW	0.98 *	0.14	0.14
2 RW	1.29 *	0.16	0.15
3 RW	0.79 *	0.13	0.12
1	1.74 **	0.094 (.088)	0.10 (.098)
2	1.90 **	0.083 (.088)	0.091 (.084)
4	1.82 **	0.099 (.089)	0.11 (.11)

* BASED ON ZYGO MECHANICAL MEASUREMENTS

** BASED ON ITEK INTERFEROGRAM ANALYSIS

( ) DATA FROM EARLIER TESTS

shown for each retroreflector. The average dihedral angle for each reworked retroreflector, based on the Zygo mechanical measurement data of Section 5.0, is also shown for reference purposes; the Itek-derived dihedral angles are about 0.5 arc sec lower (Section 6.0). The dihedral angles shown for the original retroreflectors are based on the Itek interferogram analysis of Section 3.0.

The test results are plotted in Figure 6-1, at Itek-derived dihedral angles. Comparison with the predicted results indicates that, at these lower dihedral angles, the test results are higher than the analytical results; the opposite situation occurs at the higher dihedral angles. The test results, however, fall close to the ideal predictions for the off-nominal retroreflectors (the dash-line in Figure 6-1). Results are also plotted at Zygo-measured dihedral angles.

For the original retroreflectors, the optical test data obtained in the basic test program is shown in parentheses. Comparison of this original data, with the new results, indicates only an insignificant difference, which verifies the validity of the data taken for the new reworked retroreflectors.

Typical photographic data, of the far-field pattern for each reworked retroreflector, are shown in Figure 7-7 with similar photographic data for the original retroreflectors, including those used to generate the reworked retroreflectors. The photographs are arranged by average dihedral angle, increasing from left to right and top to bottom. The increasing spread of the pattern with increasing dihedral angle, also noted in the analytical results, is obvious from this data.

New photographic data for the original retroreflectors is compared in Figure 7-8 with data taken from these same retroreflectors in the original test program. Overall intensity differences are attributed to film variations. It can be seen that the patterns are the same for each retroreflector, in a comparison between the earlier and the later test data.

The exposure time used in obtaining the basic photographic data for the add-on tests are selected as 1/250 sec, the same exposure time used in the earlier tests for a laser incident angle of 0°. To obtain photographs which show more details of the configuration of the diffraction patterns for each reworked retroreflector, photographs were also taken at minimum exposure time, 1/500 sec. These photographs, in Figure 7-9, show the characteristic "snowflake pattern", not evident in the data of Figure 7-7. The return patterns from a Zygo master cube (reflective-coated on the back surfaces) and from a GFE Apollo Flight retroreflector (uncoated) are also shown for reference purposes.

Using the photographic data, measurements were made to estimate the centroid diameter (i.e. "brightness" centroid) of the energy in the far-field

FIGURE 7-7

FAR-FIELD DIFFRACTION PATTERN COMPARSIONS

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- Isothermal-Ambient Conditions
  - Normal Laser Incident Angle
- Test Dates Noted
- Exposure Time: 1/250 sec.

S/N 3 RW
12/10/74

S/N 1 RW
12/10/74

S/N 2 RW
12/10/74

S/N 3
8/16/74

S/N 6
8/16/74

S/N 4
12/9/74

S/N 1
12/9/74

S/N 2
12/9/74

S/N 5
8/16/74

BASELINE TEST RESULTS COMPARISONS

- Far-Field Diffraction Patterns
- Isothermal-Vacuum Conditions
- Normal Laser Incident Angles
- Test Dates Noted

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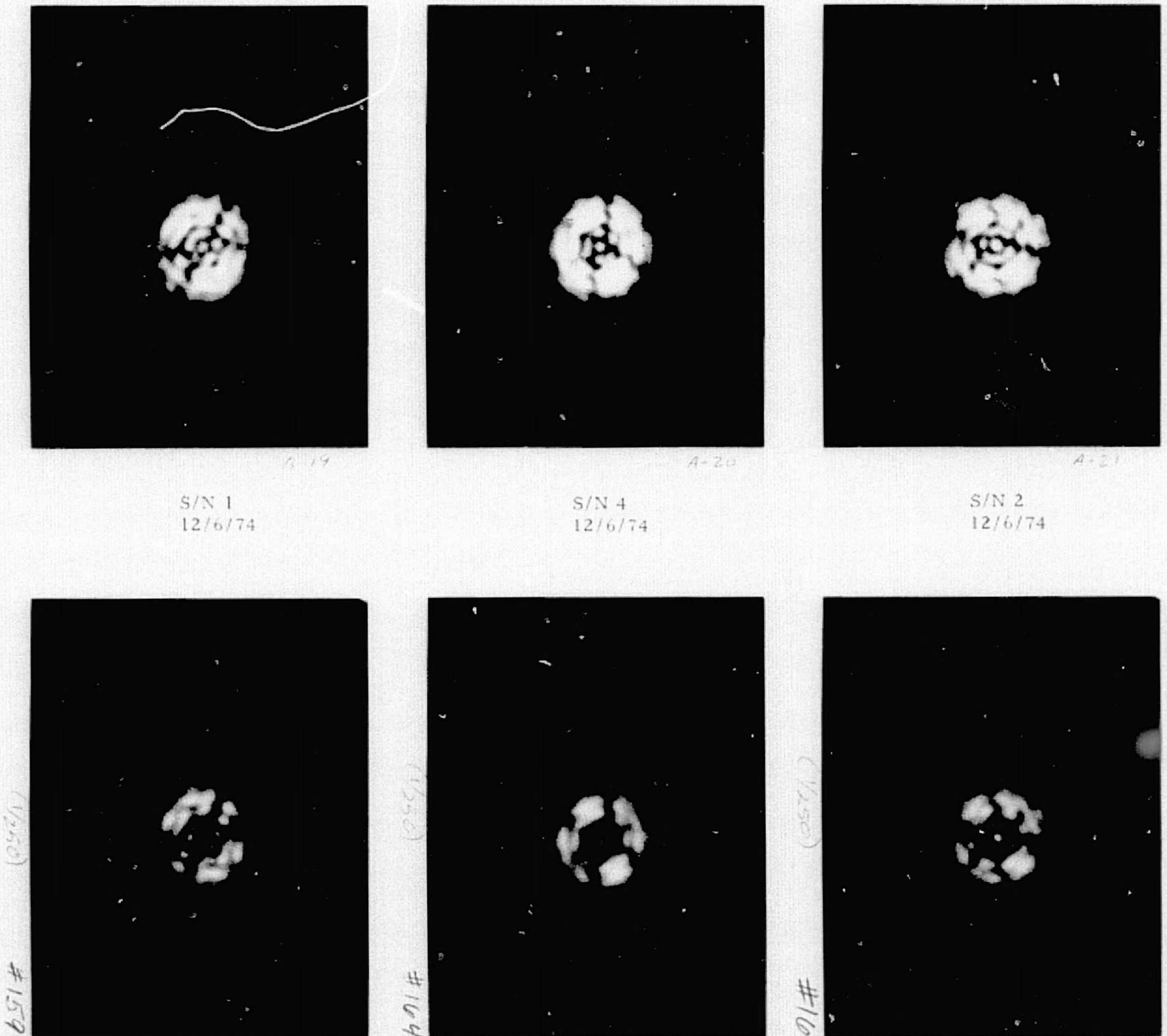
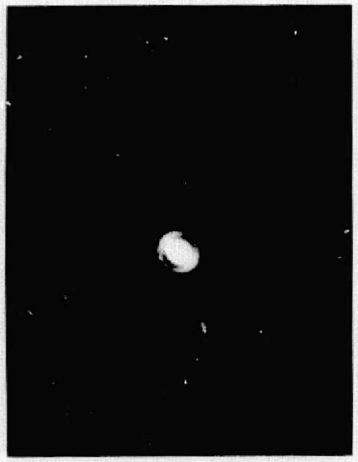


A-19	A-20	A-21
S/N 1 12/6/74	S/N 4 12/6/74	S/N 2 12/6/74
(1/250) #159	(1/250) #164	(1/250) #169
S/N 1 8/12/74	S/N 4 8/12/74	S/N 2 8/12/74

FIGURE 7-8

COMPARISON OF RETROREFLECTOR TYPES

- Isothermal-Ambient Conditions
- Normal Laser Incident Angles
- Test Date Noted



Zygo Master Cube
Exposure Time: 1/500 sec.
12/4/74

Apollo S/N 415-A
Exposure Time: 1/500 sec
10/22/74

S/N 3 RW
Exposure Time: 1/500 sec
12/10/74

S/N 1 RW
Exposure Time: 1/500 sec
12/10/74

S/N 2 RW
Exposure Time: 1/500 sec
12/10/74

FIGURE 7-9

pattern of each reworked retroreflector. These visual estimates, although accepted as not very accurate, were made to provide a comparison with similar data, obtained in the same manner, for all of the original LAGEOS test retroreflectors. The results are given in Table 7-2. They are also plotted in Figure 6-2, at Itek-derived dihedral angles and at Zygo-measurement dihedral angles.

7.4 Retainer Ring Optical Effects

A test was conducted, in the early phase of this effort,to experimentally confirm that the retainer ring, of the retroreflector mount hardware, has no effect on the optical test measurements. The test article consisted of a GFE Apollo (ALSEP) retroreflector (S/N 415-A), installed in cavity "B" of the LAGEOS test article panel, using a set of LAGEOS flight design mounting hardware. A removeable mask was installed on the front face of the panel to cover the retainer ring and to expose only the retroreflector face. Tests were run with, and without, the mask installed, Photometric and photographic data were taken with the Far-Field Diffraction Instrument (FFDI). Data was also taken for the calibration retroreflector to confirm the FFDI operation.

The results are tabulated in Table 7-3. The photographic data is shown in Figure 7-10. Based on the results shown, it can be concluded that no measureable laser return is reflected from the retainer ring and, therefore, the retainer ring has no effect on optical test measurements. Its presence is required in the mount hardware design primarily for thermal reasons, as described in detail in the basic Final Report (BSR 4159).

TABLE 7-2

SUMMARY OPTICAL TEST RESULTS

RETROREFLECTOR S/N	AVG. DIHEDRAL ANGLE (ARC SEC) *	FAR-FIELD DIFFRACTION PATTERN ENERGY CENTROID DIAMETER (ARC SEC) **
1 RW	0.98	13.2
2 RW	1.29	14.7
3 RW	0.79	12.5

* BASED ON ZYGO MECHANICAL MEASUREMENTS

** BASED ON FFDI PHOTO DATA

TABLE 7-3

EFFECT OF RETAINER RING ON OPTICAL PERFORMANCE

. TEST ARTICLE:
- ALSEP FLIGHT RETROREFLECTOR (S/N 415-A)
- INSTALLED IN CAVITY "B" OF LAGEOS TEST ARTICLE PANEL
- REMOVEABLE MASK TO EXPOSE ONLY THE RETROREFLECTOR FACE (FLAT BLACK SURFACE)

. TEST INSTRUMENTATION: - FAR-FIELD DIFFRACTION INSTRUMENT

LASER POLARIZATION: LINEAR @ 0^{o}

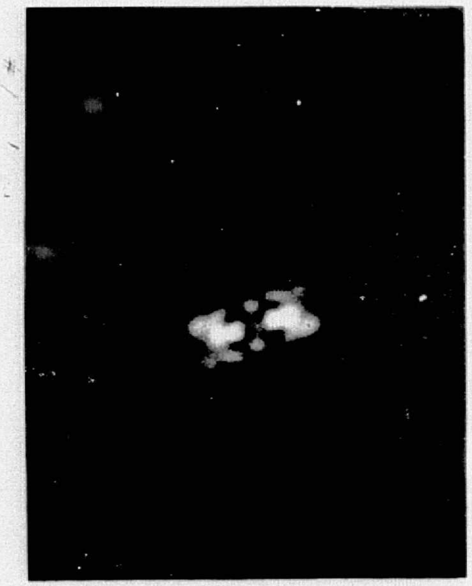
. RESULTS:

RETRO TYPE	CALIB.	ALSEP	ALSEP	ALSEP
MASK	NO.	NO	YES	NO
PHOTO NO.	1	2	3	4
LASER	.83	.83	.83	.83
FFDP-ANNULAR	.14	.14	.15	.15
RATIO-ANNULAR	.17	.18	.18	.18
RATIO-FULL FIELD	1.13	1.20	1.22	1.22
ANNULAR/FULL FIELD	.14	.15	.14	.14
BIAS	—	-.007	—	-.007

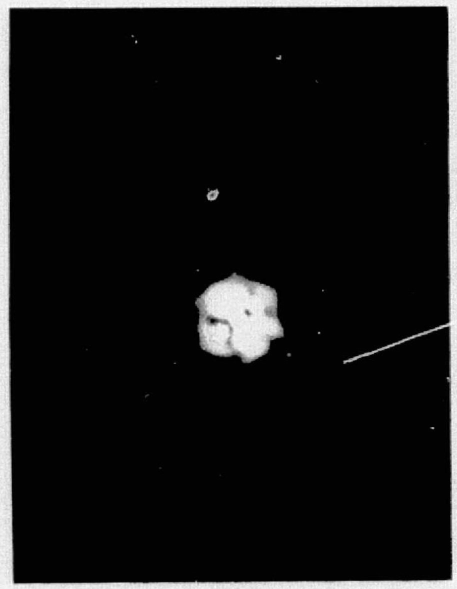
. CONCLUSIONS:

NO MEASUREABLE LASER RETURN FROM RETAINER RING

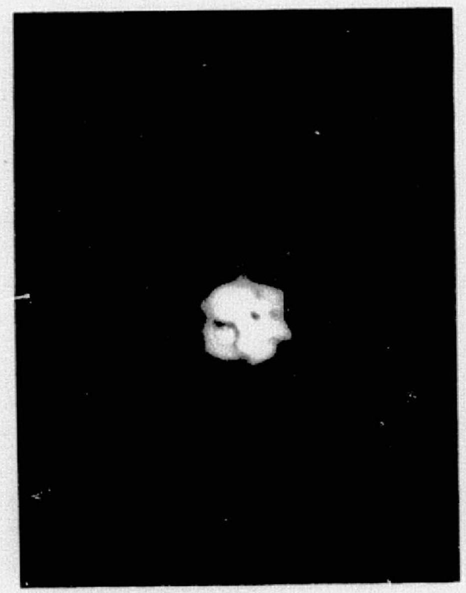
LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI



Test No. RETAINER RING TEST
Retro: CALIBRATION
Photo No. 1
Exposure Time: 1/500 SEC



Test No. RETAINER RING TEST
Retro: APOLLO (ALSEP) 415-A
Photo No. 2
Exposure Time: 1/500 SEC
RETAINER MASK NO



Test No. RETAINER RING TEST
Retro: APOLLO (ALSEP) 415-A
Photo No. 3
Exposure Time: 1/500 SEC
RETAINER MASK YES

FIGURE 7-10

8.0 EVALUATION CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations derived from the results of this study were developed in two stages and presented in Data Review Meetings at NASA/MSFC. At these meetings, the study results were reviewed and the conclusions were finalized, based on inputs from the various organizations involved in LAGEOS retroreflector performance.

8.1 Conclusions

The initial mechanical measurements effort, to redetermine the dihedral angles of the six LAGEOS test retroreflectors, provided results which indicated not only wide variations between measurements made at different organizations, but also between measurements made by different operators and at different times, in the same organization. It was concluded that mechanical measurements were unreliable and not repeatable for small (i. e. arc sec) dihedral angle measurement. This experience supports the use of interferograms as a primary means for retroreflector inspection, since interferograms provide a direct measurement of the effect of dihedral angle on the exit wavefront of the return beam.

Based on the analysis of interferograms for the original LAGEOS test retroreflectors, it was concluded that the average dihedral angle of these reflectors was actually about $90^{\circ} + 1.8$ arc sec. The average dihedral angles vary from 1.44 to 2.14 arc sec, which indicates most test retroreflectors were on the high side of the specified nominal dihedral angle of 1.5 arc sec.

The far-field intensity distribution predictions, generated as a function of dihedral angle (both nominal and off-nominal), provide the key to understanding the existing test and new analytical performance data for the LAGEOS test retroreflectors and to identifying the optimum dihedral angle for LAGEOS. This data, for ideal retroreflectors, shows that inclusion of polarization and diffraction effects results in an optimum dihedral angle of 1.35 arc sec; the effects of unequal dihedral angles, represented by the off-nominal ideal retroreflector data, leads to an optimum dihedral angle of 1.25 arc sec. The original LAGEOS dihedral angle specification was 1.5 arc sec, on the basis of geometric considerations only.

The data also provides an indication of the increase in retroreflector performance (by reducing the performance variation) for a reduction in the tolerance on the dihedral angle specification. It is obvious that, if the nominal dihedral angle is at, or near, the optimum, less performance can be gained by a reduction in tolerance. This data was included in an MSFC trade-off evaluation with the related cost increase for a reduced tolerance and the existing tolerance of $\pm$ 0.5 arc sec was retained.

Comparison of the existing test and new analytical performance data for LAGEOS test reflectors with the ideal retroreflector data illustrates a major reason for the lower performance demonstrated by the LAGEOS retroreflectors in the basic study. The dihedral angles for the LAGEOS test retroreflectors tend to be on the high-side of 1.5 arc sec,as observed previously, in the region of rapidly decreasing performance with increasing dihedral angle. Although both the test and analytical data tend to follow the shape of the ideal curve, the test data is generally lower than the analytical data, for which no reason was positively identified in the study. Use of the actual retroreflector characteristics, from interferograms, also tended to give lower performance predictions than the ideal predictions for the same average dihedral angle.

The test and analytical data for the test retroreflectors did not, however, cover the lower range of dihedral angle. It was considered necessary to confirm the ideal retroreflector predictions in this lower dihedral-angle region prior to final selection of the optimum dihedral angle. Thus, no change was made in the plan to rework three of the test retroreflectors to provide the desired additional test and analytical data. The dihedral angle requirements were selected to obtain widely-spaced data points.

The mechanical measurements and the interferometric analysis resulted in average dihedral angles, for each reworked retroreflector, which differed by about 0.5 arc sec. Also, whereas in the early dihedral angle evaluation the mechanical measurements were generally lower than the interferometric analysis results, in this more recent analysis the mechanical measurements are higher than the dihedral angle derived from the interferograms. The same measurements technique was employed by Zygo and the same analytical process was used by Itek to generate these dihedral angles. No reasonable explanation for this difference has been developed. These results have strengthened the case for interferometric measurements in the acceptance inspection of flight retroreflectors.

The test results and analytical predictions, of the retroreflector far-field annulus intensity, both show the same trend as the ideal retroreflector predictions (i.e. decreasing performance with decreasing dihedral angle, for angles less than 1.25 arc sec). The test results indicate a performance increase at these lower dihedral angles, over that obtained in tests of retroreflectors having dihedral angles greater than 1.25 arc sec. Whether plotted at the mechanically-measured angles or at the interferometrically-derived angles, the data confirms the existance of an optimum dihedral angle at about 1.25 arc sec.

Differences between the test measurements and the analytical predictions for the reworked retroreflectors and the original retroreflectors can be explained by differences in the test annulus and the analytical annulus or by differences in the test far-field intensity distribution and the analytically-derived far-field intensity distribution. Test annulus dimensions were rechecked and the FFDI scale factor was reviewed in the basic program. Insufficient test data exists to permit a detail comparison of intensity distribution for the test and analytical cases.

8.2 Recommendations

Based on the results of this study it is recommended that a dihedral angle of $90^{o} + 1.25$ arc sec ($\pm$ 0.5 arc sec) be adopted for the retroreflector specification.

It is also recommended that flight retroreflector acceptance criteria be based on interferometric determination of dihedral angle. Acceptance on the basis of optical performance criteria, as measured by a Far-Field Diffraction Instrument (FFDI),should be included at least as an option.

Measurement of the optical performance of all flight retroreflectors, by an FFDI,is recommended to verify performance for LAGEOS and to add to the present limited understanding of retroreflector characteristics.

Since unexplained anomalies still exist between analytically-determined dihedral angles and optical performance and the direct measurement of these characteristics, further investigation into these analysis and measurement techniques is recommended. The availability of a second FFDI, planned for optical testing at Perkin-Elmer during mid-1975, provides the opportunity to cross-check measurements by each FFDI, on the same retroreflectors. Measurements of far-field intensity distribution, through the use of film intensity analysis techniques or a series of annular masks of various diameters, would provide the data required for detail comparison with the predicted intensity distribution,and thus provide an understanding of the basic nature of these differences. It would be expected that changes in test instrumentation and/or analytical techniques would be identified and thus benefit future applications of retroreflectors.

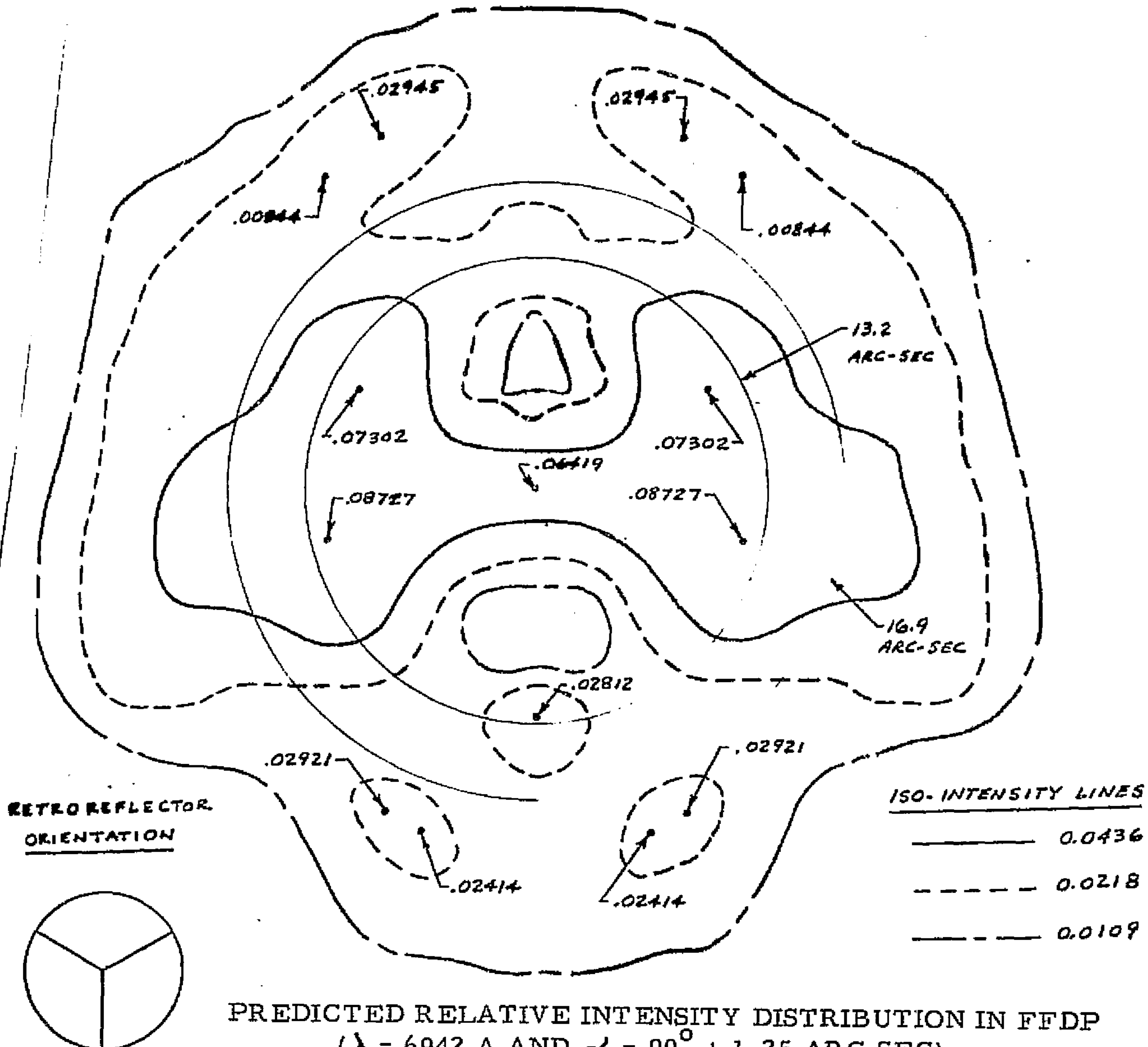
9.0 LASER WAVELENGTH EVALUATION AND DIHEDRAL ANGLE SELECTION (NASA/MSFC STUDY)

The empirical and theoretical data from the LAGEOS Performance Improvement Study, described in Sections 3 through 8 of this report, proved conclusively that a stronger return signal could be obtained if the retroreflector dihedral angle was changed from $90^{\circ}+1.5$ arc sec to $90^{\circ}+1.25$ arc sec. The analysis and testing were both performed at a laser beam wavelength of 6328 A°.

To insure that no unexpected problems were introduced by this change at other laser wavelengths, an analysis of the structure of the far-field diffraction pattern (FFDP) as a function of laser wavelength and the proposed dihedral angles was performed in the NASA/MSFC Optics Group. The wavelengths chosen were 6943 A°, 5320 A° and 3500 A°. For each of these wavelengths, the theoretical FFDP for average dihedral angles of $90^{\circ}+1.5$ arc sec and a $90^{\circ}+1.25$ arc sec were predicted. Each wavelength produced similar types of structural changes in the FFDP, with decreasing dihedral angle. These were a reduction of the overall FFDP size, an increase in the intensity near the axis, and an increase in the intensity of the maximum points. The results for wavelengths of 6943 and 3500 A° are shown in Figure 9-1 through 9-4.

Because the previous tests and analyses verified that an improvement in performance was achieved by reducing the dihedral angle for a 6328 A° wavelength, and the present analysis predicts similar changes at other wavelengths, it was concluded that the LAGEOS satellite return signal strength would be stronger at all laser wavelengths, if the dihedral angle were changed from $90^{\circ}+1.5$ arc sec to $90^{\circ}+1.25$ arc sec.

FIGURE 9-1



PREDICTED RELATIVE INTENSITY DISTRIBUTION IN FFDP
(λ = 6942 A AND α = 90° + 1.25 ARC SEC)

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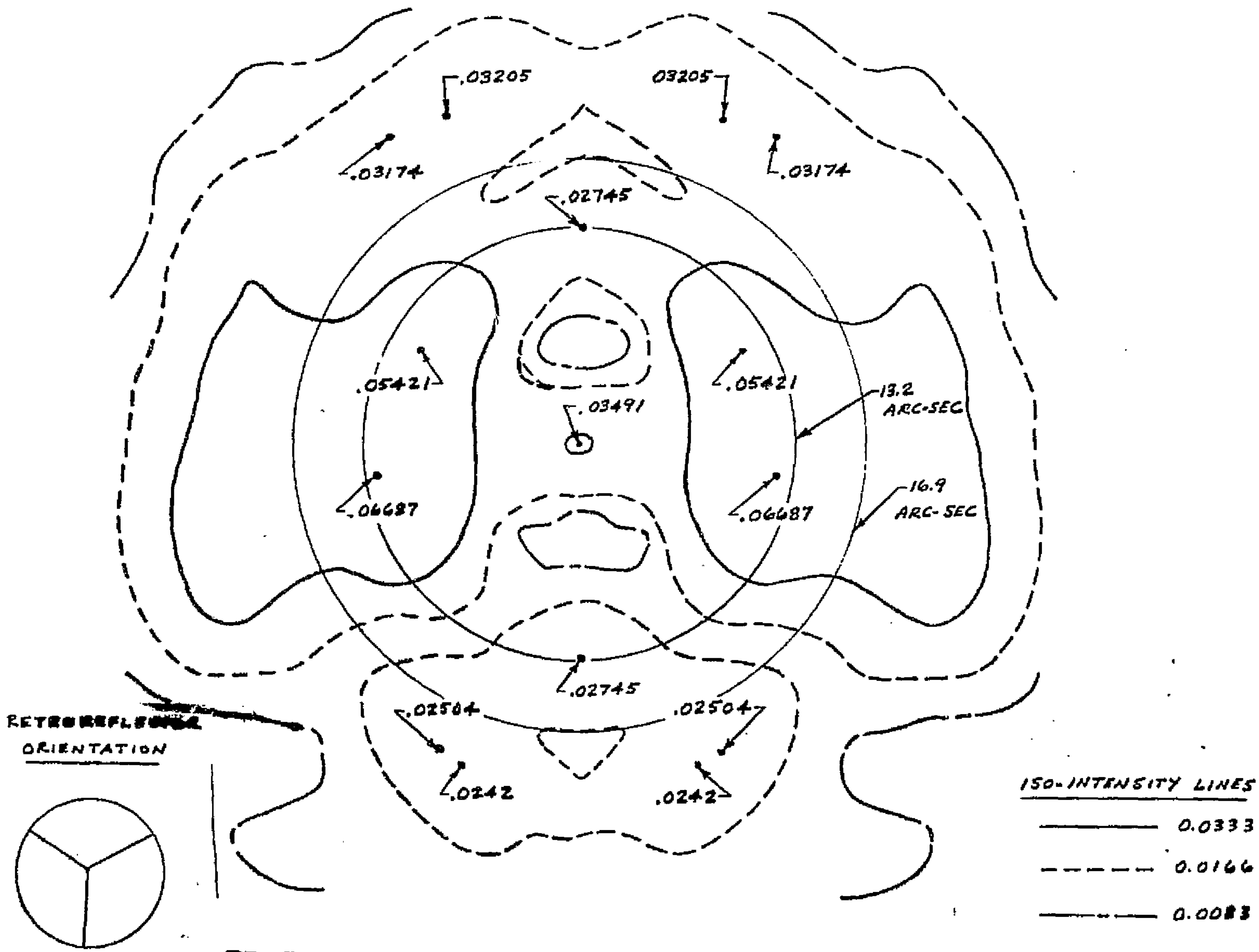
FIGURE 9-2



PREDICTED RELATIVE INTENSITY DISTRIBUTION IN FFDP
(λ = 6943 A AND α = 90° +1.5 ARC SEC)

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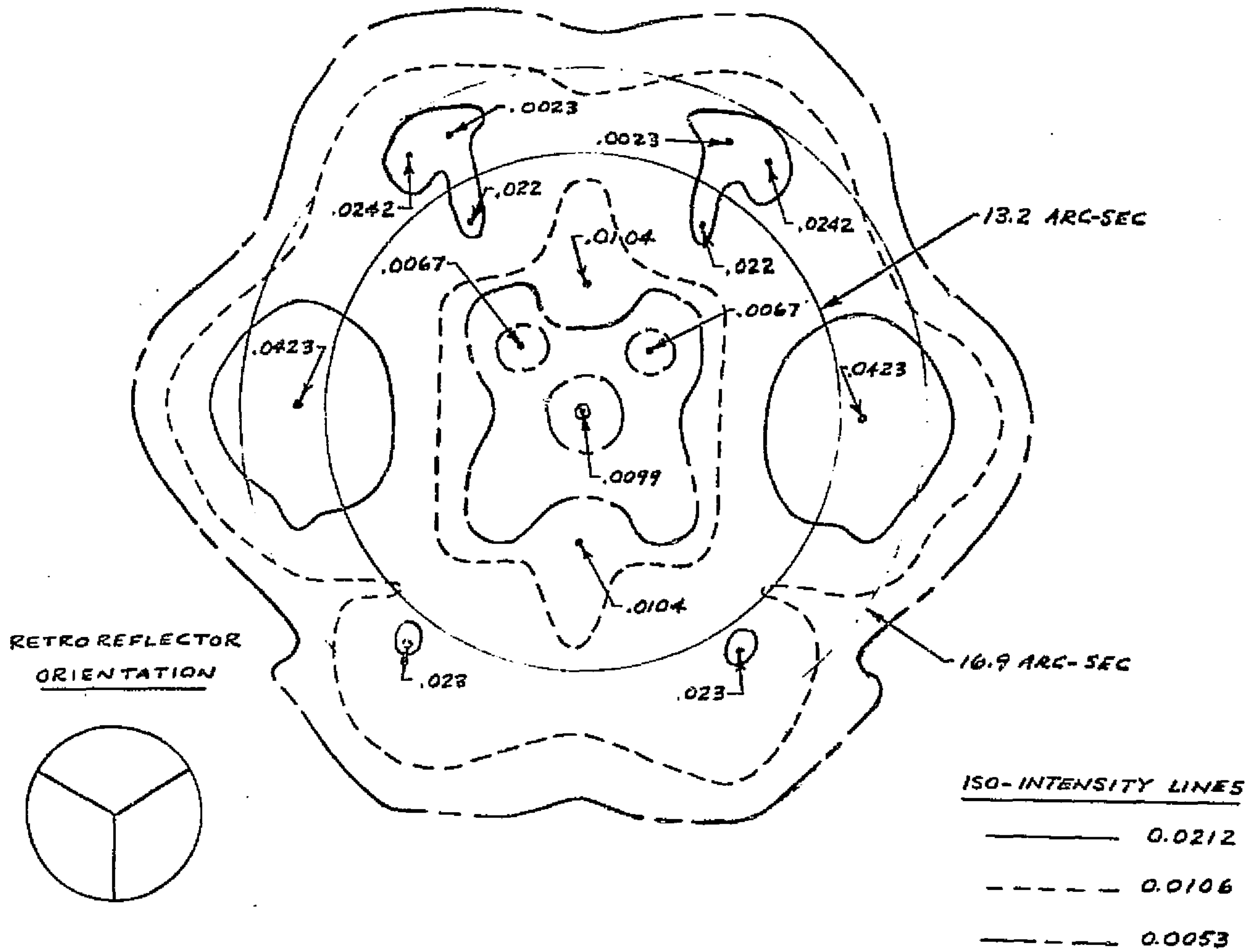
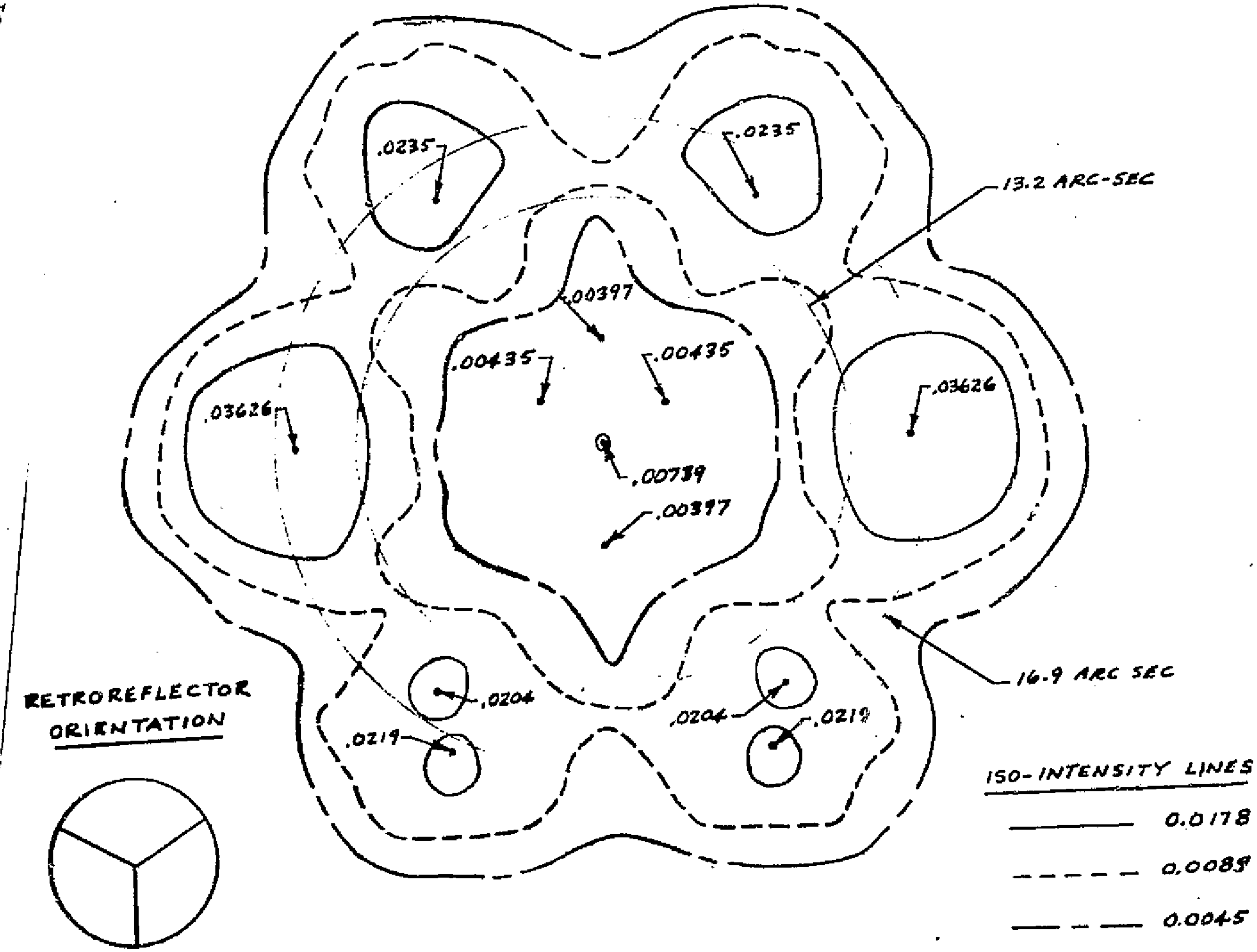
FIGURE 9-3



PREDICTED RELATIVE INTENSITY DISTRIBUTION IN FFDP
(λ = 3500 A AND α = 90° + 1.25 ARC SEC)

FIGURE 9-4



PREDICTED RELATIVE INTENSITY DISTRIBUTION IN FFDP
(λ = 3500 A AND α = 90° + 1.5 ARC SEC)

10.0 REFERENCES

The following documents are referenced in this report:

A. Study Plan - Laser Geodynamic Satellite (LAGEOS) Thermal/Optical/Vibrational Analyses and Test Program, Bendix Document LAGEOS-8, Revision C, dated 8 November 1974.

B. Final Report - Laser Geodynamic Satellite Thermal/Optical/Vibrational Analyses and Testing, Bendix Document BSR 4159, dated October 1974.

LAGEOS-48

Bendix Aerospace Systems Division

APPENDIX A

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

FIRST DATA REVIEW MEETING

AT NASA/MSFC

24 OCTOBER 1974

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

OBJECTIVES

- THROUGH MEASUREMENT, ANALYSIS AND TEST, DETERMINE THE BASIS OF THE DEMONSTRATED RETROREFLECTOR PERFORMANCE.
- IDENTIFY DIHEDRAL ANGLE CHANGES FOR RETROREFLECTOR PERFORMANCE IMPROVEMENT.
- VERIFY THE IMPROVEMENT BY ANALYSIS AND TEST.

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

TASK SUMMARY

- RETROREFLECTOR DIMENSIONAL VERIFICATION (ZYGO, ITEK, PERKIN-ELMER)

  MECHANICAL MEASUREMENT OF DIHEDRAL ANGLES

  GENERATION AND ANALYSIS OF T-G INTERFEROGRAMS TO DETERMINE DIHEDRAL ANGLES

- OPTICAL PERFORMANCE ANALYSIS (ITEK)

  DIHEDRAL ANGLE TOLERANCE ANALYSIS

  FAR-FIELD PERFORMANCE FOR MEASURED RETROREFLECTOR CHARACTERISTICS

- FIRST DATA REVIEW MEETING

  COMPARE MECHANICAL MEASUREMENTS BY DIFFERENT ORGANIZATIONS

  COMPARE MECHANICAL MEASUREMENTS WITH T-G MEASUREMENTS

  COMPARE FAR-FIELD PERFORMANCE ANALYSIS/T-G MEASUREMENTS/ TEST DATA

  SELECT RETROREFLECTORS TO BE REWORKED

  SELECT NEW DIHEDRAL ANGLE REQUIREMENTS FOR REWORK OF RETROREFLECTORS.

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

TASK SUMMARY (CONTINUED)

- REWORK THREE RETROREFLECTORS TO NEW DIHEDRAL ANGLE REQUIREMENTS (ZYGO)
    - MECHANICAL MEASUREMENTS OF DIHEDRAL ANGLES
    - GENERATE T-G INTERFEROGRAMS
- OPTICAL PERFORMANCE ANALYSIS (ITEK)
    - ANALYSIS OF T-G INTERFEROGRAMS TO DETERMINE DIHEDRAL ANGLES
    - PREDICT FAR-FIELD OPTICAL PERFORMANCE
- OPTICAL PERFORMANCE TEST (BENDIX, ZYGO)
    - MEASURE FAR-FIELD PERFORMANCE FOR REWORKED RETROREFLECTORS (3)
    - MEASURE FAR-FIELD PERFORMANCE FOR ORIGINAL RETROREFLECTORS (3)
- DATA REVIEW MEETING
    - COMPARE MECHANICAL MEASUREMENTS WITH T-G MEASUREMENTS
    - COMPARE FAR-FIELD PERFORMANCE ANALYSIS RESULTS (EFFECT OF REWORK)
    - COMPARE FAR-FIELD PERFORMANCE ANALYSIS WITH TEST RESULTS
    - COMPARE FAR-FIELD PERFORMANCE TEST RESULTS
        - ORIGINAL RETROREFLECTORS (NEW RESULTS & PREV. RESULTS)
        - REWORKED RETROREFLECTORS (NEW RESULTS & PREV. RESULTS)

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

STATUS

ZYGO

ANALYSIS T-G INTERFEROGRAMS (6)	COMPLETE	
REMEASURE DIHEDRAL ANGLES (3) (MECHANICAL) (ZYGO & MOORE)	COMPLETE	(#1, 2, 4)

PERKIN-ELMER

MEASURE DIHEDRAL ANGLES (3) (MECHANICAL)	COMPLETE	(#3, 5, 6)
GENERATE & ANALYZE T-G INTERFEROGRAMS (3)	COMPLETE	(#3, 5, 6)

ITEK

GENERATE & ANALYZE T-G INTERFEROGRAMS (6)	COMPLETE
ANALYZE ZYGO T-G INTERFEROGRAMS (6)	COMPLETE
OPTICAL ANALYSIS (FAR-FIELD) (6) BASED ON T-G INTERFEROGRAMS	COMPLETE
TOLERANCE OPTICAL ANALYSIS (FAR-FIELD)	COMPLETE

NOTE: ( ) REFERS TO NO. OF RETROREFLECTORS

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

SCHEDULE

FIRST DATA REVIEW MEETING		24 OCT. 1974
ZYGO		
REWORK RETROREFLECTORS (3)	START:	25 OCT. 1974
	COMPLETE:	29 NOV. 1974
GENERATE T-G INTERFEROGRAMS	COMPLETE:	29 NOV. 1974
ITEK		
ANALYZE ZYGO	START:	2 DEC. 1974
T-G INTERFEROGRAMS (3)	COMPLETE:	10 DEC. 1974
OPTICAL ANALYSIS (FAR-FIELD) BASED ON T-G INTERFEROGRAMS	COMPLETE:	13 DEC. 1974
COMPARISON OPTICAL MODEL WITH SAO MODEL	COMPLETE:	13 DEC. 1974
BENDIX		
RECEIVE RETROREFLECTORS FROM P. E.		28 OCT. 1974
RECEIVE REWORKED RETROREFLECTORS FROM ZYGO		2 DEC. 1974
OPTICAL TESTS	COMPLETE:	6 DEC. 1974
EVALUATE TEST DATA	COMPLETE:	10 DEC. 1974

FINAL DATA REVIEW MEETING: TO BE SCHEDULED

EFFECT OF RETAINER RING ON OPTICAL PERFORMANCE

- TEST ARTICLE:
  - ALSEP FLIGHT RETROREFLECTOR (S/N 415-A)
  - INSTALLED IN CAVITY "B" OF LAGEOS TEST ARTICLE PANEL
  - REMOVEABLE MASK TO EXPOSE ONLY THE RETROREFLECTOR FACE (FLAT BLACK SURFACE)

- TEST INSTRUMENTATION: - FAR-FIELD DIFFRACTION INSTRUMENT

  LASER POLARIZATION: LINEAR @ 0^{o}

- RESULTS:

RETRO TYPE	CALIB.	ALSEP	ALSEP	ALSEP
MASK	NO.	NO	YES	NO
PHOTO NO.	1	2	3	4
LASER	.83	.83	.83	.83
FFDP-ANNULAR	.14	.14	.15	.15
RATIO-ANNULAR	.17	.18	.18	.18
RATIO-FULL FIELD	1.13	1.20	1.22	1.22
ANNULAR/FULL FIELD	.14	.15	.14	.14
BIAS	—	-.007	—	-.007

- CONCLUSIONS:

  NO MEASUREABLE LASER RETURN FROM RETAINER RING

ZYGO

22 October 1974

TASKS CARRIED OUT BY ZYGO

I. Reduced Original T-G Interferograms for 6 cube corners.

II. Remeasured Dihedral Angles.

III. Had Moore Special Tool Measure Dihedral Angles.

IV. Analyzed and Tabulated the Results of Tasks I, II and III.

ZYGO

22 October 1974

DIHEDRAL ANGLE MEASUREMENTS

Cube Corner I.D.#	Dihedral Angle	Moore (arc sec)*	Zygo (arc sec)* Operator #1	Zygo (arc sec)* Operator #2
1	R1-R2	2.14±0.02	2.10±0.02	2.05±0.03
	R3-R2	2.00±0.07	1.67±0.06	1.89±0.07
	R3-R1	1.72±0.09	1.55±0.05	1.75±0.03
2	R1-R2	1.68±0.04	1.33±0.02	1.63±0.05
	R3-R2	1.84±0.02	1.38±0.06	1.81±0.05
	R3-R1	1.76±0.05	1.38±0.03	1.76±0.04
4	R1-R2	1.82±0.02	1.68±0.05	1.46±0.03
	R3-R2	1.80±0.03	1.24±0.02	1.30±0.05
	R3-R1	1.80±0.06	1.23±0.02	1.41±0.02

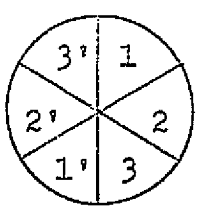
*The average angles and standard deviations above are based on five (5) measurements of each cube corner.

ZYGO

22 October 1974

ZYGO INTERFEROGRAM REDUCTION

Cube Corner I.D.#	$\Phi_{11'}$ (arc sec)	$\Phi_{22'}$ (arc sec)	$\Phi_{33'}$ (arc sec)
1	17.9	21.0	18.0
2	16.0	15.2	12.3
3	17.0	13.9	11.8
4	15.2	15.7	15.6
5	23.5	21.7	18.6
6	15.5	15.4	13.4



$\Phi nn'$ = angle between the n and n' output wavefronts

ZYGO

22 October 1974

SUMMARY OF ZYGO INTERFEROGRAM REDUCTION

I.

Cube Corner I.D.#	$(\Phi_{11'} + \Phi_{22'} + {}_{33'})/3$ (arc sec)	Equivalent Average Dihedral Angle*
1	18.97	2.00
2	14.81	1.55
4	15.47	1.63

II.
Average $\Phi_{nn'}$ for all 3 Cube Corners = 16.42 arc sec.

III.
Equivalent Average Dihedral Angle = 1.73 arc sec.

* Based on $\langle\Phi_{nn'}\rangle = 4N \left(\frac{8}{3}\right)^{\frac{1}{2}}$ (Average Dihedral Angle), or where N=refractive index

$\langle\Phi_{nn'}\rangle = 9.51 \times$ (Average Dihedral Angle) for fused silica

22 October 1974

COMPARISON OF FFDP DATA
AND
ZYGO INTERFEROGRAM REDUCTION

Cube Corner I.D.#		Diameter of FFDP Centroid
1	$\Phi_{11'}=17.9$ arc sec	22.0 arc sec
	$\Phi_{22'}=21.0$ arc sec	
	$\Phi_{33'}=18.0$ arc sec	
2	$\Phi_{11'}=16.0$ arc sec	19.8 arc sec
	$\Phi_{22'}=15.2$ arc sec	
	$\Phi_{33'}=13.3$ arc sec	
3	$\Phi_{11'}=17.0$ arc sec	17.6 arc sec
	$\Phi_{22'}=15.9$ arc sec	
	$\Phi_{33'}=11.8$ arc sec	
4	$\Phi_{11'}=15.2$ arc sec	20.6 arc sec
	$\Phi_{22'}=15.7$ arc sec	
	$\Phi_{33'}=15.6$ arc sec	
5	$\Phi_{11'}=23.5$ arc sec	23.5 arc sec
	$\Phi_{22'}=21.7$ arc sec	
	$\Phi_{33'}=18.6$ arc sec	
6	$\Phi_{11'}=15.5$ arc sec	18.4 arc sec
	$\Phi_{22'}=15.4$ arc sec	
	$\Phi_{33'}=13.4$ arc sec	

$\langle\Phi_{nn'}\rangle=16.58$ arc sec | $\langle\Phi FFDP\rangle=20.3$ arc sec

Equiv. Dih $\measuredangle=1.74$ arc sec | Equiv. Dih. $\measuredangle=2.14$ arc sec

ZYGO

22 October 1974

DIHEDRAL ANGLE SUMMARY

(Average of 9 Dihedral Angles for Cube Corners 1, 2 and 4)

Source	Method	Average Dihedral Angle
Itek	Interferogram Reduction	1.82 ± 0.07
Moore	Mechanical Measurement	1.84 ± 0.05 *
Zygo	Interferogram Reduction	1.73 ± 0.07
Zygo	Mechanical Measurement	1.60 ± 0.06 *

* Standard deviation based on spread of measured dihedral angles

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Moore Special Tool Co., Inc.

Certificate of Accuracy

FOR
ZYGO CORPORATION
OF
3 CORNER PRISMS AND (1) 90° MASTER CUBE

Corner Prisms identified as 1, 2 and 4 were calibrated on Moore Small Angle Divider S/N SAD110-8-2160-87. Angular deviation from 90° is shown on Pages 2, 3 and 4 attached.

Corner Prisms were set on a leveling table on the small angle divider and the faces calibrated were aligned with the vertical axis of a photo electric auto-collimator. Angular deviation was determined by nulling the auto-collimator and rotating the small angle divider through ° arc. Readings were taken from the small angle divider.

Small angle divider S/N SAD110-8-2160-87 was calibrated 10 Oct 74 and is traceable to three bureaus of Standards including our National Bureau of Standards.

We estimate the accuracy of determination to be 0.3 arc seconds.

Certification No. 696

Date: October 10, 1974 Chief Inspector R. L. Parnell

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ZYGO

CUBE # 1 DATE: October 14, 1974

ARC SECONDS

1. MASTER	0.00	TIME:	1:00 PM
1 - 2	+2.20		
3 - 2	+1.90		
3 - 1	+1.40		
2. MASTER	-0.10	TIME:	2:00 PM
1 - 2	+2.10		
3 - 2	+2.30		
3 - 1	+1.70		
3. MASTER	-0.10	TIME:	3:00 PM
1 - 2	+2.20		
3 - 2	+2.00		
3 - 1	+2.00		
4. MASTER	-0.10	TIME:	4:00 PM
1 - 2	+2.00		
3 - 2	+1.80		
3 - 1	+1.70		
5. MASTER	-0.10	TIME:	8:00 AM 10-15-74
1 - 2	+2.20		
3 - 2	+2.00		
3 - 1	+1.80		

MOORE SPECIAL TOOL CO., INC.

H. A. Randlett

Signature

ZYGO

CUBE # 2 DATE: October 15, 197

ARC SECONDS

1.	MASTER	-0.10	TIME:	8:30 AM
	1 - 2	+1.70		
	3 - 2	+1.90		
	3 - 1	+1.90		
2.	MASTER	0.00	TIME:	9:10 AM
	1 - 2	+1.70		
	3 - 2	+1.80		
	3 - 1	+1.80		
3.	MASTER	0.00	TIME:	9:45 AM
	1 - 2	+1.50		
	3 - 2	+1.80		
	3 - 1	+1.70		
4.	MASTER	-0.10	TIME:	10:20 AM
	1 - 2	+1.80		
	3 - 2	+1.80		
	3 - 1	+1.60		
5.	MASTER	0.00	TIME:	10:45 AM
	1 - 2	+1.70		
	3 - 2	+1.90		
	3 - 1	+1.80		

MOORE SPECIAL TOOL CO., INC.

H. A. Randlett

Signature

ZYGO

CUBE # 4 DATE: October 15, 1974

ARC SECONDS

1.	MASTER	0.00	TIME: 11:30 AM
	1 - 2	+1.80	
	3 - 2	+1.80	
	3 - 1	+2.00	
2.	MASTER	-0.10	TIME: 12:30 PM
	1 - 2	+1.80	
	3 - 2	+1.80	
	3 - 1	+1.70	
3.	MASTER	-0.10	TIME: 1:15 PM
	1 - 2	+1.80	
	3 - 2	+1.80	
	3 - 1	+1.70	
4.	MASTER	0.00	TIME: 2:00 PM
	1 - 2	+1.80	
	3 - 2	+1.90	
	3 - 1	+1.70	
5.	MASTER	-0.10	TIME: 2:30 PM
	1 - 2	+1.90	
	3 - 2	+1.70	
	3 - 1	+1.90	

MOORE SPECIAL TOOL CO., INC.

H. A. Randlett

Signature

ZYGO

CUBE # 1 DATE: 10/12

1. MASTER -.26 TIME: 10:45

   1 - 2 +2.12

   3 - 2 +1.53

   3 - 1 +1.44

2. MASTER -.31 TIME: 10:5[illegible]

   1 - 2 +2.06

   3 - 2 +1.89

   3 - 1 +1.76

3. MASTER -.34 TIME: 11:09

   1 - 2 +2.10

   3 - 2 +1.69

   3 - 1 +1.50

4. MASTER -.30 TIME: 11:16

   1 - 2 +2.05

   3 - 2 +1.74

   3 - 1 +1.54

5. MASTER -.33 TIME: 11:30

   1 - 2 +2.18

   3 - 2 +1.52

   3 - 1 +1.50

DJ

Signature
Operator #1

ZYGO

CUBE # 2 DATE: 10/12

1. MASTER −.29 TIME: 8:15

1 - 2 +1.30

3 - 2 +1.24

3 - 1 +1.31

2. MASTER −.27 TIME: 8:30

1 - 2 +1.42

3 - 2 +1.60

3 - 1 +1.49

3. MASTER −.33 TIME: 8:47

1 - 2 +1.27

3 - 2 +1.39

3 - 1 +1.42

4. MASTER −.25 TIME: 9:00

1 - 2 +1.32

3 - 2 +1.40

3 - 1 +1.40

5. MASTER −.24 TIME: 9:15

1 - 2 +1.35

3 - 2 +1.29

3 - 1 +1.30

PV

Signature
Operator #1

ZYGO

CUBE # 4 DATE: 10/2

1.	MASTER	-.29	TIME: 9:30
	1 - 2	+1.76	
	3 - 2	+1.29	
	3 - 1	+1.20	
2.	MASTER	-.32	TIME: 9:[illegible]
	1 - 2	+1.45	
	3 - 2	+1.19	
	3 - 1	+1.53	
3.	MASTER	-.35	TIME: 10:00
	1 - 2	+1.79	
	3 - 2	+1.22	
	3 - 1	+1.20	
4.	MASTER	-.38	TIME: 10:19
	1 - 2	+1.71	
	3 - 2	+1.25	
	3 - 1	+1.21	
5.	MASTER	-.39	TIME: 10:30
	1 - 2	+1.69	
	3 - 2	+1.23	
	3 - 1	+1.19	

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Signature
Operator #1

ZYGO

CUBE # 1 DATE: 12/19/74

1. MASTER	-.11	TIME:	7:40 AM
1 - 2	+1.99		
3 - 2	+1.75		
3 - 1	+1.83		
2. MASTER	.08	TIME:	8:10
1 - 2	+2.03		
3 - 2	+2.07		
3 - 1	+1.66		
3. MASTER	-.12	TIME:	8:40
1 - 2	+2.[illegible]		
3 - 2	+1.68		
3 - 1	+1.71		
4. MASTER	-.08	TIME:	8:52
1 - 2	+2.00		
3 - 2	+1.95		
3 - 1	+1.84		
5. MASTER	-.08	TIME:	9:05
1 - 2	+2.03		
3 - 2	+2.02		
3 - 1	+1.72		

WJ

Signature

Operator #2

ZYGO

CUBE # 2 DATE: 10/10/74

1.	MASTER	-.10	TIME: 9:15 AM
	1 - 2	+1.62	
	3 - 2	+1.75	
	3 - 1	+1.74	
2.	MASTER	-.11	TIME: 9:30
	1 - 2	+1.73	
	3 - 2	+1.88	
	3 - 1	+1.78	
3.	MASTER	-.10	TIME: 9:45
	1 - 2	+1.75	
	3 - 2	+1.78	
	3 - 1	+1.68	
4.	MASTER	-.12	TIME: 9:55
	1 - 2	+1.60	
	3 - 2	+1.99	
	3 - 1	+1.92	
5.	MASTER	-.12	TIME: 10:10
	1 - 2	+1.46	
	3 - 2	+1.65	
	3 - 1	+1.67	

NL

Signature
Operator #2

ZYGO

CUBE # 4 DATE: 10/21/74

1. MASTER -.20 TIME: 11:05
1 - 2 +1.44
3 - 2 +1.29
3 - 1 +1.10

2. MASTER -.16 TIME: 11:30
1 - 2 +1.46
3 - 2 +1.17
3 - 1 +1.37

3. MASTER -.21 TIME: 12:10
1 - 2 +1.40
3 - 2 +1.48
3 - 1 +1.38

4. MASTER -.20 TIME: 12:25
1 - 2 +1.44
3 - 2 +1.20
3 - 1 +1.45

5. MASTER -.20 TIME: 12:55
1 - 2 +1.58
3 - 2 +1.35
3 - 1 +1.43

NL

Signature
Operator #2

LAGEOS

DIHEDRAL ANGLE IMPROVEMENT PROGRAM

PREPARED UNDER

CONTRACT TO

BENDIX AEROSPACE SYSTEMS DIVISION

24 OCTOBER 1974

Itek

TOPICS

- PURPOSE/OBJECTIVES
- TASKS
- SUMMARY OF RESULTS
- INTERFEROMETRY OF CUBES
- PREDICTION OF DIHEDRAL ANGLES
- PREDICTION OF FAR FIELD PATTERN
- TOLERANCE ANALYSIS
- CONCLUSIONS

PURPOSE/OBJECTIVES

RESOLVE CONTRADICTIONS IN TEST RESULTS

- PREDICT DIHEDRAL ANGLES FROM INTERFEROGRAMS
  - COMPARE WITH INDEPENDENT MEASUREMENTS
- PREDICT FAR FIELD PATTERN FROM INTERFEROGRAMS
  - COMPARE WITH MEASURED DATA
- RECOMMEND REVISED DIHEDRAL ANGLE
- ANALYZE REWORKED CUBES

TASKS

- EVALUATE EXISTING CUBES
  - ANALYZE ZYGO INTERFEROGRAMS
    - PREDICT DIHEDRAL ANGLES
  - TEST CUBES IN TWYMAN-GREEN INTERFEROMETER
  - ANALYZE ITEK INTERFEROGRAMS
    - PREDICT DIHEDRAL ANGLES
    - PREDICT FAR FIELD PATTERN
- TOLERANCE ANALYSIS (.9 - 2.1 ARC-SEC)
- MODEL COMPARISON (SAO)
- EVALUATE REWORKED CUBES
  - ANALYZE ZYGO INTERFEROGRAMS
    - PREDICT DIHEDRAL ANGLES
    - PREDICT FAR FIELD PATTERN

SUMMARY - DIHEDRAL ANGLE

		AVERAGE DIHEDRAL ANGLE (ARC-SEC)
***	ITEK INTERFEROGRAMS	1.77
***	ZYGO INTERFEROGRAMS	1.86
*	ITEK FFDP	1.98
**	BENDIX FFDP	2.14

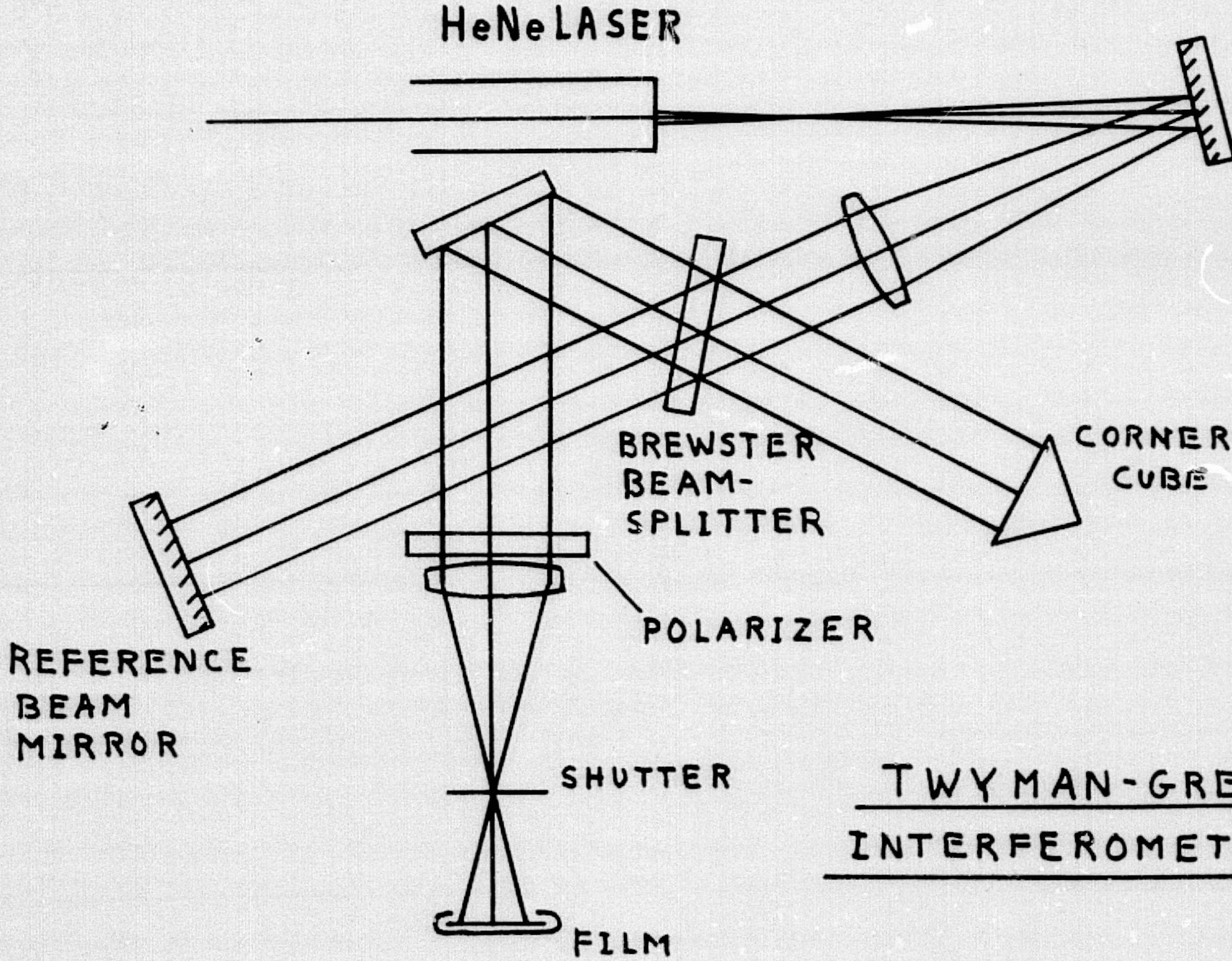
*Based on far field pattern predicted from interferograms.
**Based on far field pattern photograph measurement.
***Analyzed by Itek.

SUMMARY - FAR FIELD DIFFRACTION PATTERN

	AVERAGE PERCENT ENERGY IN 13.2 - 16.9 ARC-SEC ANNULUS	AVERAGE ANNULUS DIAMETER (ARC-SEC)
ITEK INTERFEROGRAM	14.3	18.0
BENDIX MEASUREMENT	9.7	20.3

SUMMARY - TOLERANCE STUDY

- PERCENT ENERGY IN 13.2 - 16.9 ARC-SEC ANNULUS VARIES FROM 13.0 TO 18.5 FOR DIHEDRAL ANGLES OF .9-2.1 ARC-SEC
- PEAK PERCENT ENERGY OCCURS AT ABOUT 1.35 ARC-SEC DIHEDRAL ANGLE.
- ANNULUS DIAMETER VARIES FROM 12.4 TO 22.0 ARC-SEC FOR DIHEDRAL ANGLES OF .9 - 2.1 ARC-SEC.
- OFF-NOMINAL CUBE (.0, +.5, -.5 ARC-SEC ERRORS) INCREASES ANNULUS DIAMETER BY UP TO 1.0 ARC-SEC AND CHANGES PERCENT ENERGY BY UP TO 0.7.



TWYMAN-GREEN INTERFEROMETER

TEST PROCEDURE

1. CLEAN AND MOUNT CORNER CUBE.
2. TILT CORNER CUBE ~1 DEGREE TO AVOID GLINT.
3. ORIENT POLARIZER.
4. WAIT 20 MINUTES AFTER LAST HANDLING.
5. ORIENT FRINGES PERPENDICULAR TO EACH REAL EDGE.
6. PHOTOGRAPH INTERFEROGRAM.
7. DATA REDUCTION.

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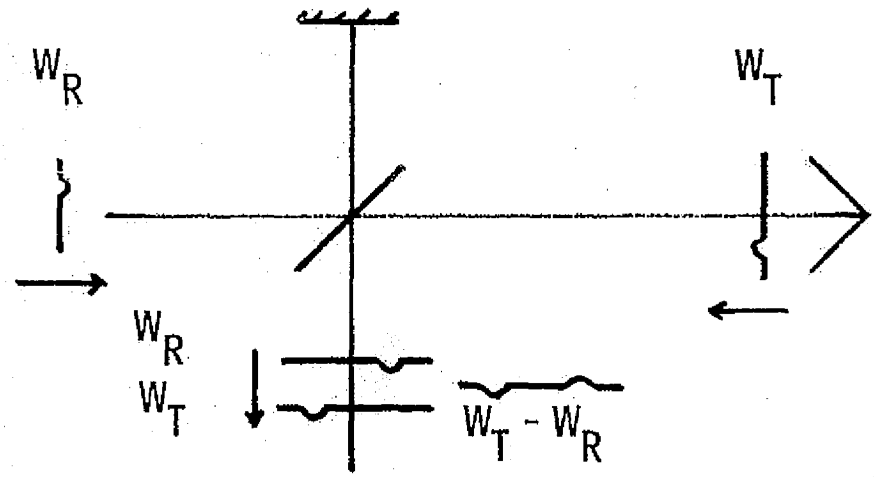
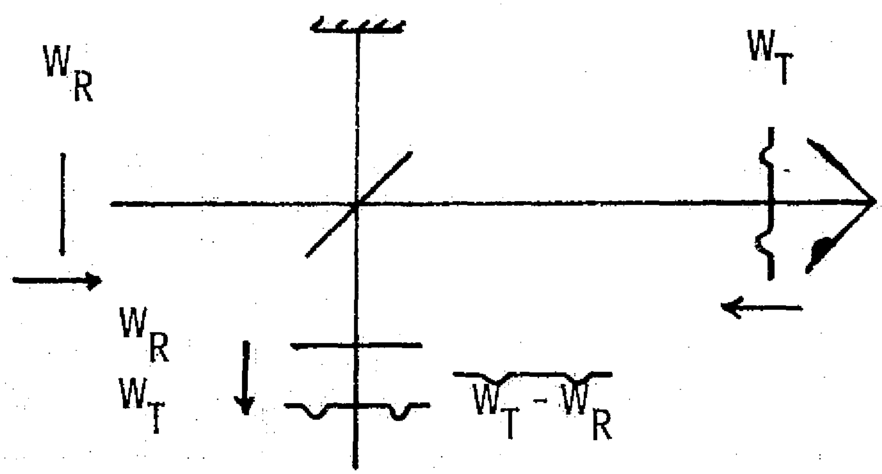
NTERFEROGRAMS OF RETROREFLECTOR #3

INTERFEROMETRY OF RETROREFLECTORS



INTERFEROMETER ERROR
RADIALLY ANTI-SYMMETRIC



RETROREFLECTOR ERROR
RADIALLY SYMMETRIC

ANALYSIS OF RETROREFLECTOR INTERFEROGRAMS

MEASURED WAVEFRONT:	$W(x, y)$
RETROREFLECTOR ERROR:	$1/2 \left[W(x, y) + W(-x, -y)\right]$
INTERFEROMETER ERROR:	$1/2 \left[W(x, y) - W(-x, -y)\right]$

ANALYSIS OF RETROREFLECTOR INTERFEROGRAMS (CONTINUED)

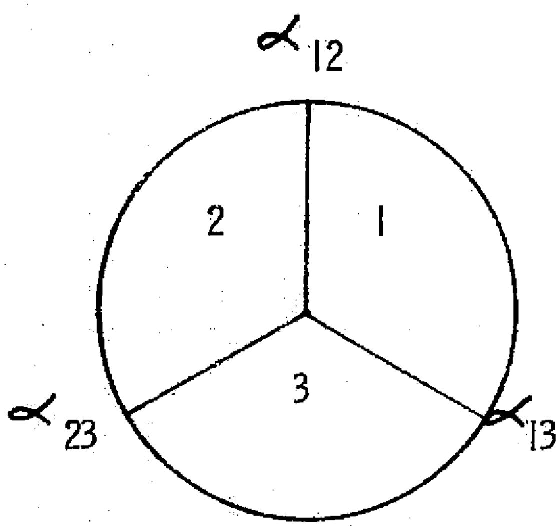
FAR FIELD PATTERN

- MEASURED PHASE IS FOR COMPONENT PARALLEL TO INPUT.
- USE THEORETICAL INTENSITY VARIATIONS.
- ADD THEORETICAL PHASE SHIFTS FOR PERPENDICULAR COMPONENT.

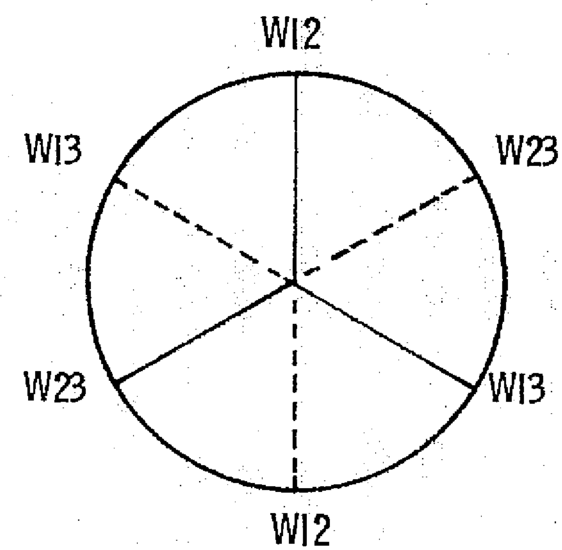
DIHEDRAL ANGLE

- FIT PLANE THROUGH EACH SEXTANT TO GET AVERAGE SLOPE.
- CALCULATE DIHEDRAL ANGLES.

CALCULATION OF DIHEDRAL ANGLES FROM INTERFEROGRAM



Cube



Wavefront

$$\alpha_{12} = \frac{1}{\sqrt{2}\, nD} \left[W_{13} + W_{23} - W_{12} \right]$$

$$\alpha_{13} = \frac{1}{\sqrt{2}\, nD} \left[W_{23} + W_{12} - W_{13} \right]$$

$$\alpha_{23} = \frac{1}{\sqrt{2}\, nD} \left[W_{12} + W_{13} - W_{23} \right]$$

n = index
D = diameter

INTERFEROMETRIC MEASUREMENT OF DIHEDRAL ANGLES (arc-sec)

Cube	Interferogram 1			2			3			Average			Ave
1	1.38	1.71	1.87	1.53	1.68	2.01	1.63	1.90	1.98	1.51	1.76	1.95	1.74
2	1.62	2.19	2.03	1.64	1.91	1.82	1.77	2.00	2.08	1.68	2.03	1.98	1.90
3	1.32	1.30	1.61	1.30	1.38	1.59	1.38	1.53	1.53	1.33	1.40	1.58	1.44
4	1.83	1.67	1.87	1.86	1.87	1.76	1.86	1.72	1.92	1.85	1.75	1.85	1.82
5	2.24	2.38	2.01	2.23	2.28	1.94	2.19	2.10	1.88	2.22	2.25	1.94	2.14
6	1.76	1.64	1.51	1.50	1.68	1.59	1.56	1.44	1.65	1.61	1.59	1.58	1.59
										Average			1.77

($1\sigma \approx .07$ Arc-Sec)

COMPARISON OF DIHEDRAL ANGLES ON CUBES 1, 2, AND 4

Cube	*Itek Interferograms	*Zygo Interferograms	Moore Mechanical Measurements
1	1.51 1.76 1.95	2.44 1.84 2.04	2.14 2.00 1.72
2	1.68 2.03 1.98	1.98 1.76 0.98	1.68 1.84 1.76
4	1.85 1.75 1.85	2.02 1.31 1.65	1.82 1.80 1.80
Average	1.82	1.78	1.84

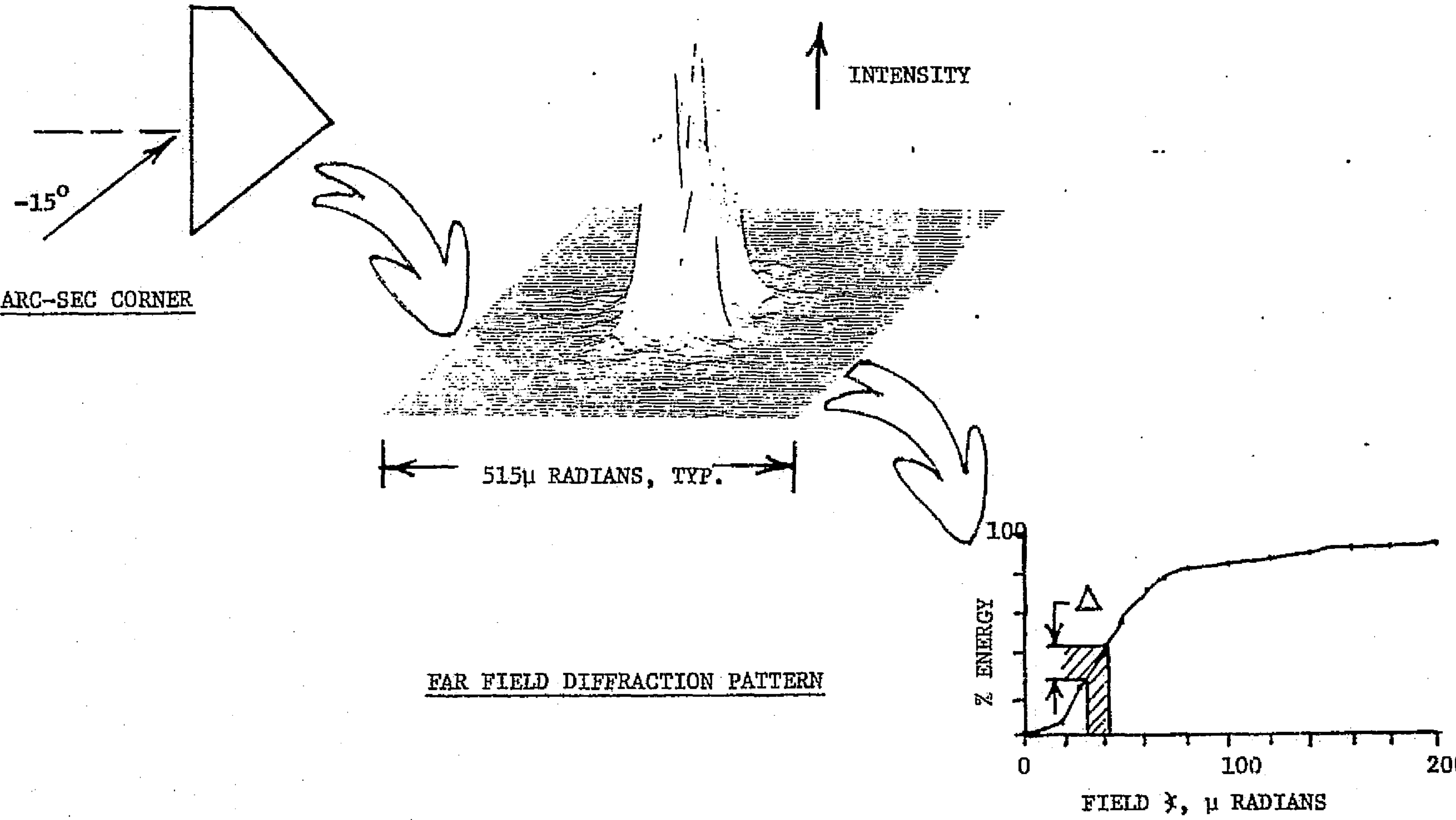
*Analyzed by Itek.

COMPARISON OF AVERAGE DIHEDRAL ANGLE (arc-sec)

Cube	*** Itek Interferogram	*** Zygo Interferogram	*Itek FFDP	**Bendix FFDP
1	1.74	2.11	1.96	2.32
2	1.90	1.57	2.13	2.08
3	1.44	1.78	1.74	1.85
4	1.82	1.66	1.96	2.17
5	2.14	2.31	2.30	2.48
6	1.59	1.71	1.78	1.94
Average	1.77	1.86	1.98	2.14

*Based on far field pattern predicted from interferograms.
**Based on far field pattern photograph measurement.
***Analyzed by Itek.

FAR-FIELD CHARACTERISTICS



1.5 ARC-SEC CORNER

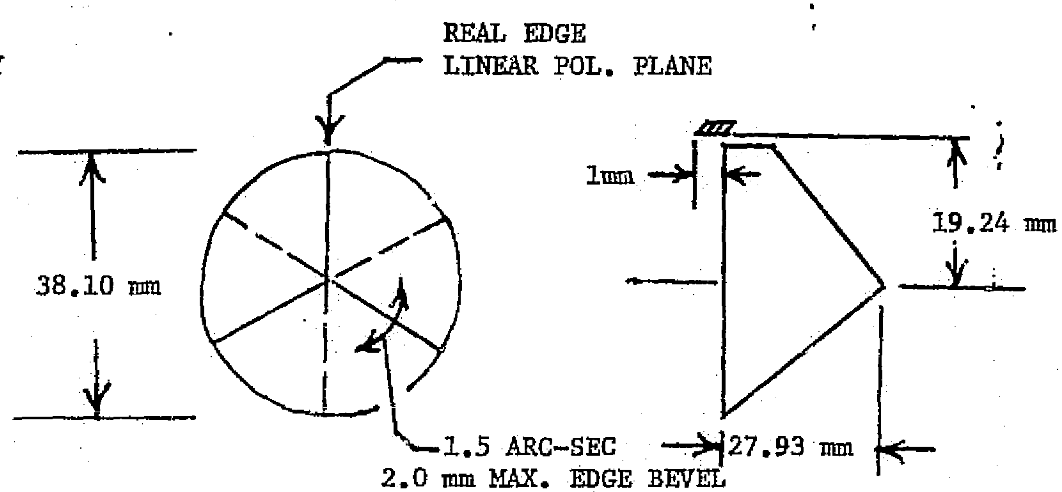
FAR FIELD DIFFRACTION PATTERN

ENCIRCLED ENERGY

ASSUMPTIONS/INPUTS

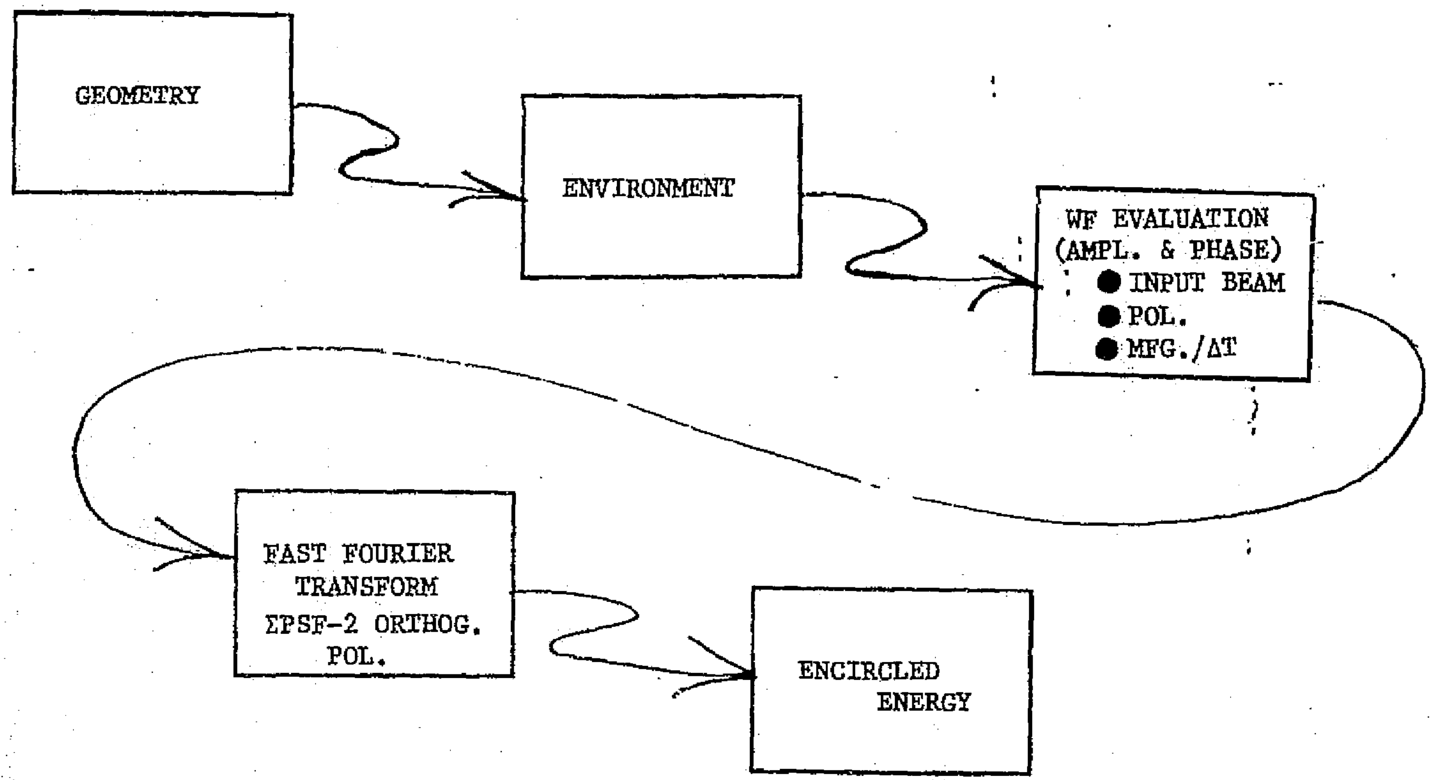
- **MATERIAL**
  - T-19 SUPRASIL 1 (SPECIAL)
  - AMERSIL DATA – N(λ), $\partial n/\partial T$ (λ,T,P) → 7 to 8.5 x 10^{-6}/°C
  - HOMOSIL, CONSERVATIVE

- **GEOMETRY**



- **LASER**
  - 6328Å, FLAT WF, CENTERED
  - 20% GAUSSIAN VARIATION OVER 50 mm DIAMETER

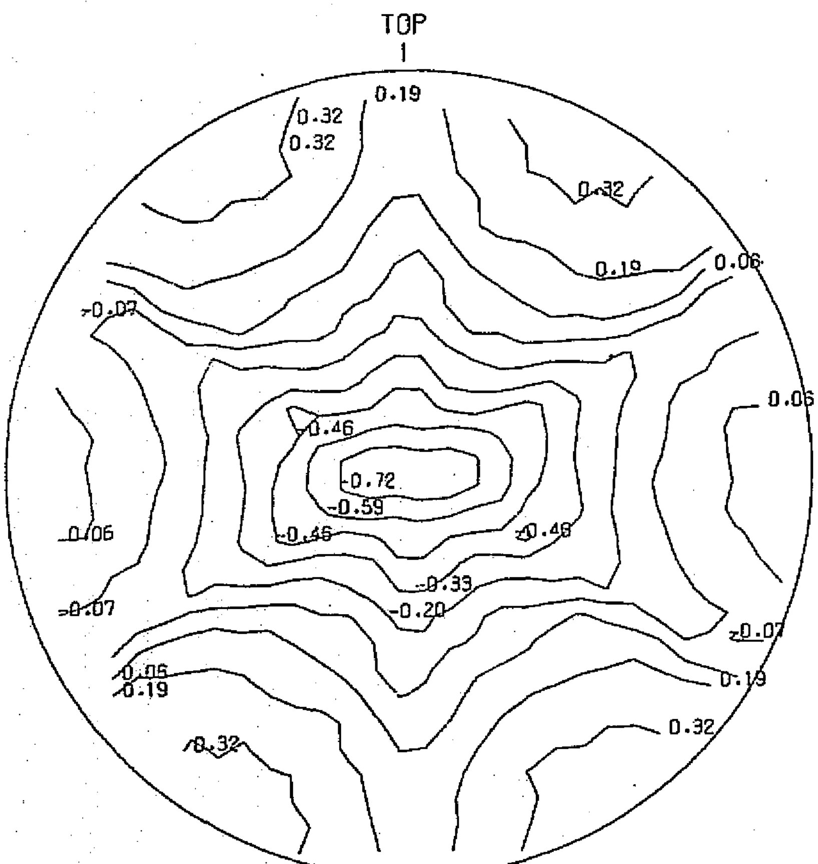
TECHNIQUES/MODEL



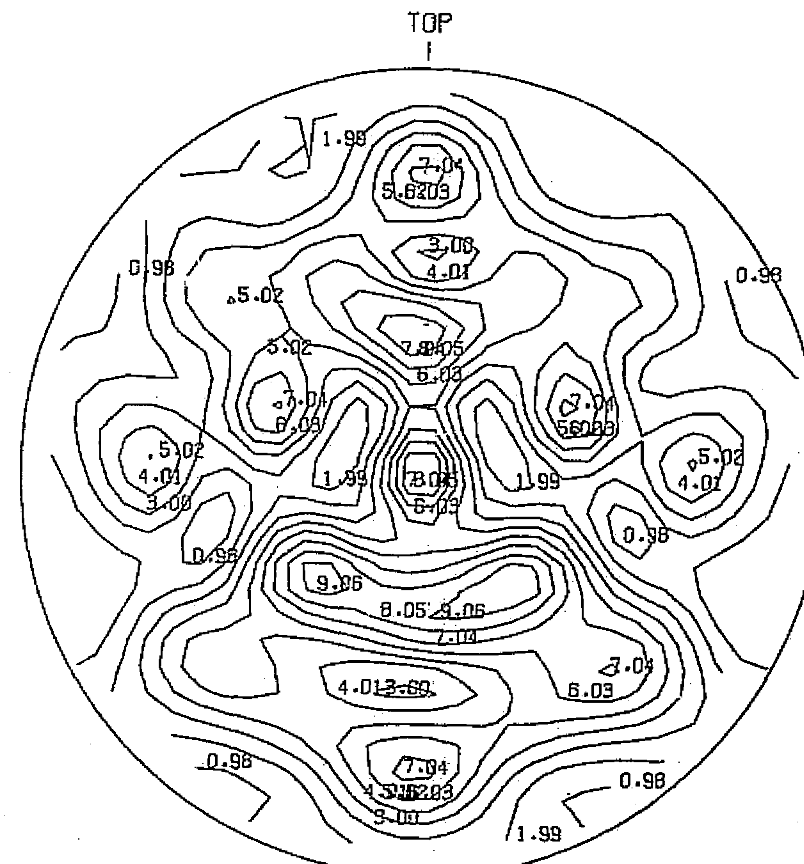
ACCURACY ~ 1% IN ENCIRCLED ENERGY

WAVEFRONT AND FAR FIELD DIFFRACTION PATTERNS
FROM RETROREFLECTOR #3*

Wavefront Plot
Q Polarization

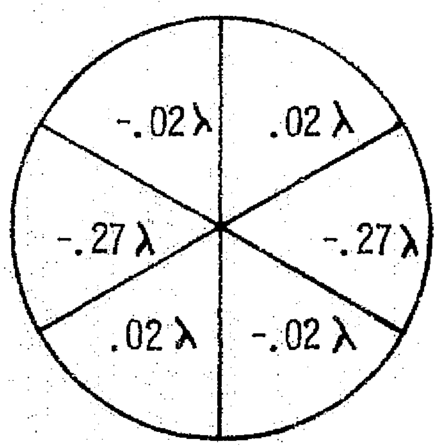


Intensity Distribution
Central 129 Microradians



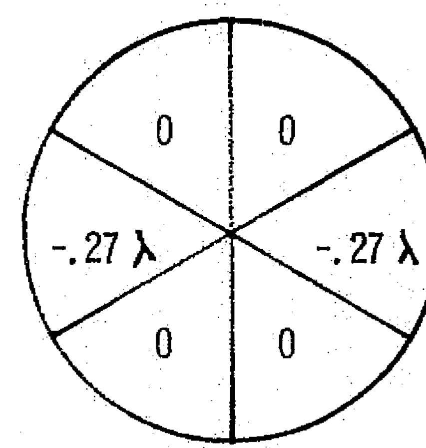
*Data is obtained from an average of three interferograms.

PHASE SHIFT DUE TO POLARIZATION



INTERFEROMETRIC
MEASUREMENT

($1\sigma = .02\lambda$)



THEORETICAL

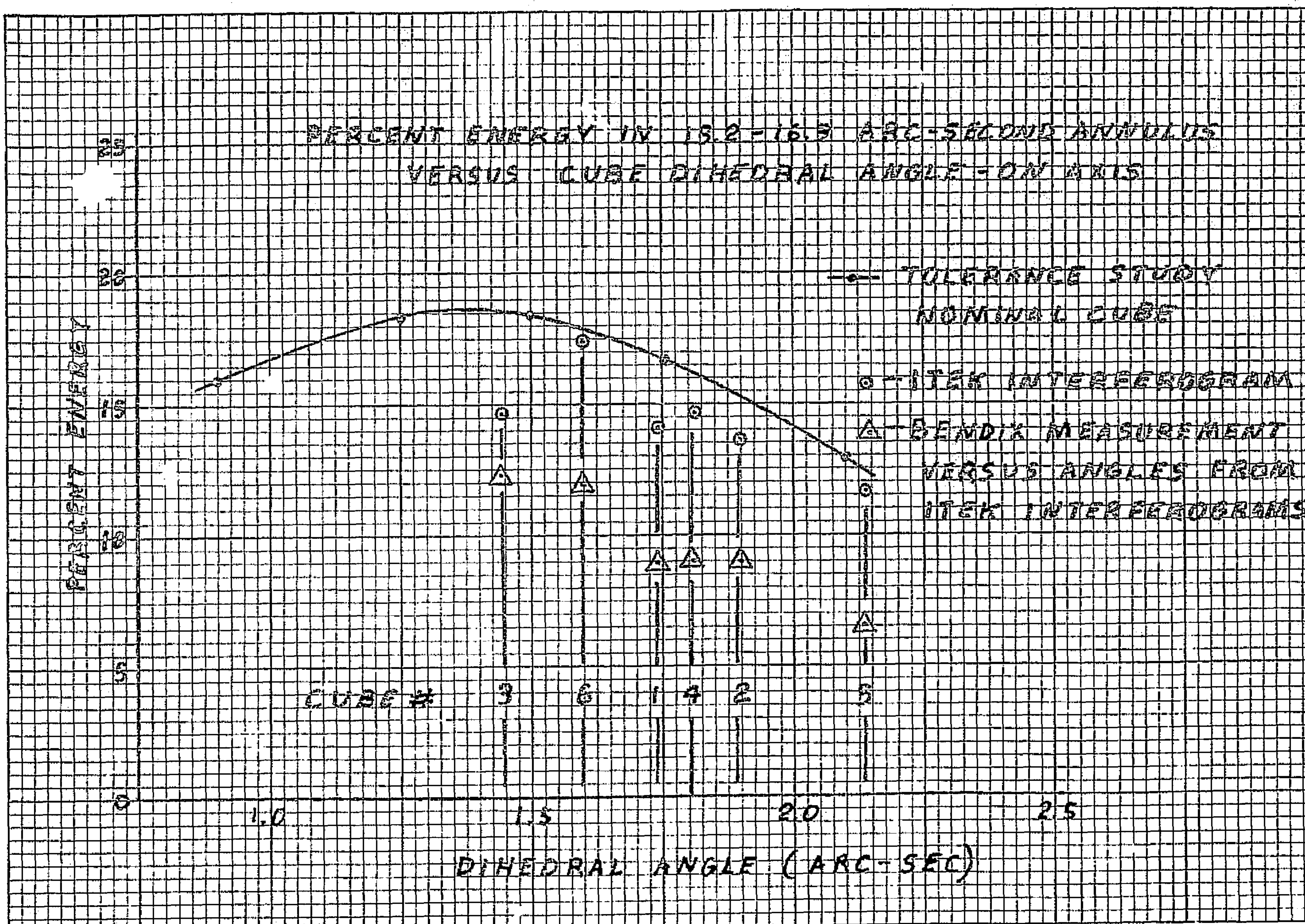
FAR FIELD CHARACTERISTICS OF LAGEOS RETROREFLECTOR - ON-AXIS

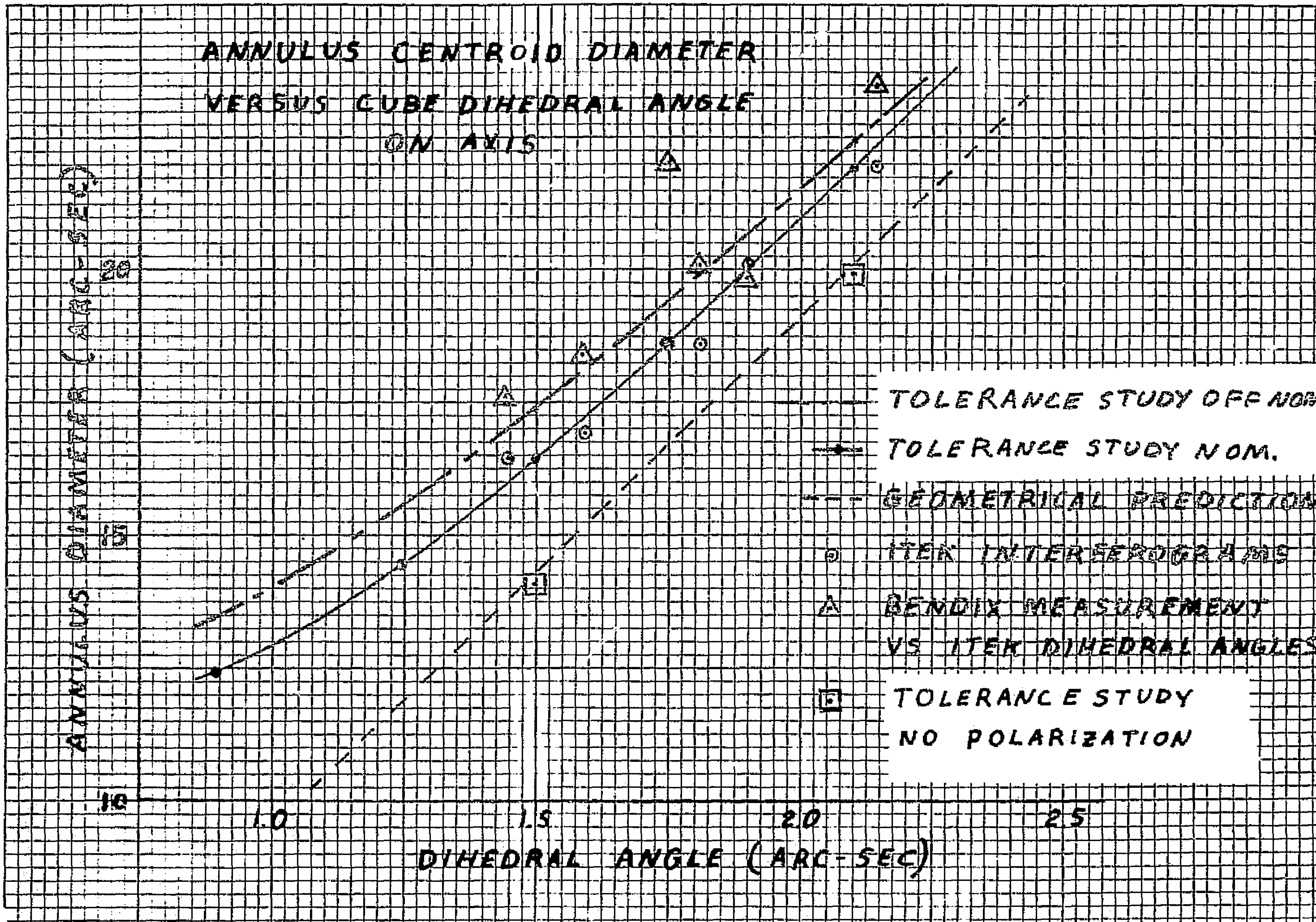
Cube #	Percent Energy 13.2 - 16.9 Arc-Sec: Itek Interferogram	Percent Energy 13.2 - 16.9 Arc-Sec: Bendix Measurement	Annulus Diameter (Arc-Sec): Itek Interferogram	Annulus Diameter (Arc-Sec): Bendix Measurement
1	14.0	8.9	18.6	22.0
2	13.6	8.9	20.2	19.8
3	14.7	12.4	14.4	17.6
4	14.6	9.0	18.6	20.6
5	11.7	6.7	21.9	23.5
6	17.4	12.0	14.4	18.4
Average	14.3	9.7	18.0	20.3

TOLERANCE STUDY
Encircled Energy & Apparent
Annulus Diameter
On-Axis

Case	Percent Energy 13.2 - 16.9 Arc-Sec	Apparent Annulus Diameter (Arc-Sec)
0.9 Arc-Sec Nominal Cube	16.0	12.4
* 0.9 Arc-Sec Off Nominal Cube	16.7	13.4
1.25 Arc-Sec Nominal Cube	18.3	14.4
1.5 Arc-Sec Nominal Cube	18.5	16.5
* 1.5 Arc-Sec Off Nominal Cube	18.2	17.3
1.75 Arc-Sec Nominal Cube	16.8	18.6
2.1 Arc-Sec Nominal Cube	13.0	22.0
* 2.1 Arc-Sec Off Nominal Cube	12.3	22.4

*.0, +.5, -.5 Arc-Sec Errors


PERCENT ENERGY IN 13.2-16.5 ARC-SECOND ANNULUS
VERSUS CUBE DIHEDRAL ANGLE - ON AXIS
TOLERANCE STUDY
NOMINAL CUBE
ITEK INTERFEROGRAM
BENDIX MEASUREMENT
VERSUS ANGLES FROM
ITEK INTERFEROGRAMS
PERCENT ENERGY
25
20
15
10
5
0
CUBE #
3
6
1
4
2
5
1.0
1.5
2.0
2.5
DIHEDRAL ANGLE (ARC-SEC)


ANNULUS CENTROID DIAMETER
VERSUS CUBE DIHEDRAL ANGLE
ON AXIS
ANNULUS DIAMETER (ARC-SEC)
20
15
10
1.0
1.5
2.0
2.5
DIHEDRAL ANGLE (ARC-SEC)
TOLERANCE STUDY OFF NOM.
TOLERANCE STUDY NOM.
GEOMETRICAL PREDICTION
ITEK INTERFEROGRAMS
BENDIX MEASUREMENT
VS ITEK DIHEDRAL ANGLES
TOLERANCE STUDY
NO POLARIZATION

SUMMARY

- AVERAGE DIHEDRAL ANGLE IS 1.8 ARC-SEC.
- AVERAGE FAR FIELD ANNULUS DIAMETER IS 18.0 ARC-SEC.
- PEAK ENERGY IN 13.2 - 16.9 ARC-SEC ANNULUS OCCURS FOR A 1.35 ARC-SEC CUBE.
- .0, +.5, -.5 ARC-SEC ERRORS INCREASE ANNULUS DIAMETER SLIGHTLY.
- MEASURED FFDP SHOWS CONSISTENTLY HIGH ANNULUS DIAMETER AND LOW PERCENT ENERGY IN 13.2 - 16.9 ARC-SEC ANNULUS.

PRELIMINARY CONCLUSIONS/RECOMMENDATIONS

- FAR FIELD ANNULUS IS LARGER THAN GEOMETRICAL PREDICTION DUE TO DIFFRACTION/POLARIZATION.
- NOMINAL DIHEDRAL ANGLES SHOULD BE REDUCED TO 1.25 ARC-SEC.
- ANALYZE AND TEST REWORKED CUBES AS PLANNED.
- CONSIDER ANALYSIS FOR OTHER INCIDENT ANGLES AND WAVE-LENGTHS.

COMPOSITE

PRELIMINARY CONCLUSIONS/RECOMMENDATIONS *

- O INTERFEROMETRIC MEASUREMENT OF DIHEDRAL ANGLES AGREES WITH MECHANICAL MEASUREMENT
- O PREDICTED FFDP DIFFRACTION PATTERNS AGREE WITH MEASURED PATTERNS CLOSER THAN PREVIOUS PREDICTIONS
- O FAR FIELD ANNULUS IS LARGER THAN GEOMETRICAL PREDICTION DUE TO DIFFRACTION/POLARIZATION
- O NOMINAL DIHEDRAL ANGLES SHOULD BE REDUCED TO 1.25 ARC - SEC.
- O ANALYZE AND TEST REWORKED CUBES AS PLANNED
- O CONSIDER ANALYSIS FOR OTHER INCIDENT ANGLES AND WAVE LENGTHS

* Coordinated between Zygo, Itek and Bendix

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

FINAL DATA REVIEW MEETING

AT NASA/MSFC

18 DECEMBER 1974

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

OBJECTIVES

- THROUGH MEASUREMENT, ANALYSIS AND TEST, DETERMINE THE BASIS OF THE DEMONSTRATED RETROREFLECTOR PERFORMANCE.
- IDENTIFY DIHEDRAL ANGLE CHANGES FOR RETROREFLECTOR PERFORMANCE IMPROVEMENT.
- VERIFY THE IMPROVEMENT BY ANALYSIS AND TEST.

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

TASK SUMMARY

- RETROREFLECTOR DIMENSIONAL VERIFICATION (ZYGO, ITEK, PERKIN-ELMER)

  MECHANICAL MEASUREMENT OF DIHEDRAL ANGLES

  GENERATION AND ANALYSIS OF T-G INTERFEROGRAMS TO DETERMINE DIHEDRAL ANGLES

- OPTICAL PERFORMANCE ANALYSIS (ITEK)

  DIHEDRAL ANGLE TOLERANCE ANALYSIS

  FAR-FIELD PERFORMANCE FOR MEASURED RETROREFLECTOR CHARACTERISTICS

- FIRST DATA REVIEW MEETING

  COMPARE MECHANICAL MEASUREMENTS BY DIFFERENT ORGANIZATIONS

  COMPARE MECHANICAL MEASUREMENTS WITH T-G MEASUREMENTS

  COMPARE FAR-FIELD PERFORMANCE ANALYSIS/T-G MEASUREMENTS/ TEST DATA

  SELECT RETROREFLECTORS TO BE REWORKED

  SELECT NEW DIHEDRAL ANGLE REQUIREMENTS FOR REWORK OF RETROREFLECTORS.

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

TASK SUMMARY (CONTINUED)

- REWORK THREE RETROREFLECTORS TO NEW DIHEDRAL ANGLE REQUIREMENTS (ZYGO)
  - MECHANICAL MEASUREMENTS OF DIHEDRAL ANGLES
  - GENERATE T-G INTERFEROGRAMS
- OPTICAL PERFORMANCE ANALYSIS (ITEK)
  - ANALYSIS OF T-G INTERFEROGRAMS TO DETERMINE DIHEDRAL ANGLES
  - PREDICT FAR-FIELD OPTICAL PERFORMANCE
- OPTICAL PERFORMANCE TEST (BENDIX, ZYGO)
  - MEASURE FAR-FIELD PERFORMANCE FOR REWORKED RETROREFLECTORS (3)
  - MEASURE FAR-FIELD PERFORMANCE FOR ORIGINAL RETROREFLECTORS (3)
- DATA REVIEW MEETING
  - COMPARE MECHANICAL MEASUREMENTS WITH T-G MEASUREMENTS
  - COMPARE FAR-FIELD PERFORMANCE ANALYSIS RESULTS (EFFECT OF REWORK)
  - COMPARE FAR-FIELD PERFORMANCE ANALYSIS WITH TEST RESULTS
  - COMPARE FAR-FIELD PERFORMANCE TEST RESULTS
    - ORIGINAL RETROREFLECTORS (NEW. RESULTS & PREV. RESULTS)
    - REWORKED RETROREFLECTORS (NEW RESULTS & PREV. RESULTS)

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

STATUS

ZYGO

ANALYSIS T-G INTERFEROGRAMS (6)	COMPLETE	
REMEASURE DIHEDRAL ANGLES (3) (MECHANICAL) (ZYGO & MOORE)	COMPLETE	(#1, 2, 4)

PERKIN-ELMER

MEASURE DIHEDRAL ANGLES (3) (MECHANICAL)	COMPLETE	(#3, 5, 6)
GENERATE & ANALYZE T-G INTERFEROGRAMS (3)	COMPLETE	(#3, 5, 6)

ITEK

GENERATE & ANALYZE T-G INTERFEROGRAMS (6)	COMPLETE
ANALYZE ZYGO T-G INTERFEROGRAMS (6)	COMPLETE
OPTICAL ANALYSIS (FAR-FIELD) (6) BASED ON T-G INTERFEROGRAMS	COMPLETE
TOLERANCE OPTICAL ANALYSIS (FAR-FIELD)	COMPLETE

NOTE: ( ) REFERS TO NO. OF RETROREFLECTORS

LAGEOS

RETROREFLECTOR PERFORMANCE IMPROVEMENT PROGRAM

SCHEDULE

FIRST DATA REVIEW MEETING		24 OCT. 1974
ZYGO		
REWORK RETROREFLECTORS (3)	COMPLETE	(#3, 5, 6)
GENERATE T-G INTERFEROGRAMS	COMPLETE	
ITEK		
ANALYZE ZYGO T-G INTERFEROGRAMS (3)	COMPLETE	
OPTICAL ANALYSIS (FAR-FIELD) BASED ON T-G INTERFEROGRAMS	COMPLETE	
COMPARISON OPTICAL MODEL WITH SAO MODEL	COMPLETE	
BENDIX		
RECEIVE RETROREFLECTORS FROM P. E.	COMPLETE	(#1, 2, 4)
RECEIVE REWORKED RETROREFLECTORS FROM ZYGO	COMPLETE	(#1RW, 2RW, 3RW)
OPTICAL TESTS	COMPLETE	
EVALUATE TEST DATA	COMPLETE	
FINAL DATA REVIEW MEETING		18 DECEMBER 1974

CONCLUSIONS AND RECOMMENDATIONS

FIRST DATA REVIEW MEETING - 24 OCTOBER 1974

- MECHANICAL AND INTERFEROMETRIC MEASUREMENTS AGREE ON AN AVERAGE BASIS.

- DIHEDRAL ANGLES FOR S/N 1 - S/N 6 RETROREFLECTOR, AVERAGE 1.75 - 1.80 ARC SEC.

- WIDE VARIATIONS IN MECHANICAL MEASUREMENTS SUPPORT INTERFEROMETRIC MEASUREMENTS FOR INSPECTION PURPOSES.

- FAR-FIELD DIFFRACTION PATTERN ENERGY CENTROID DIAMETER IS LARGER THAN EXPECTED FROM GEOMETRIC PREDICTIONS, DUE PRIMARILY TO POLARIZATION EFFECTS. OFF-NOMINAL DIHEDRAL ANGLES AND WAVE-FRONT DEVIATION RESULT IN ADDITIONAL INCREASE OF DIAMETER

- PREDICTED OPTIMUM DIHEDRAL ANGLE IS ABOUT 1.25 ARC SEC FOR LAGEOS ANNULUS OF 13.2 - 16.9 ARC SEC DIAMETERS.

- REWORK RETROREFLECTORS S/N 3, 5 AND 6 TO AVERAGE DIHEDRAL ANGLES OF $90^\circ + 0.75$, + 1.0 AND 1.25 ARC SEC.

- CONDUCT OPTICAL ANALYSIS AND TESTS OF REWORKED RETROREFLECTORS TO PROVIDE OPTICAL PERFORMANCE FOR VERIFICATION AND SELECTION OF OPTIMUM DIHEDRAL ANGLE.

- MAKE MECHANICAL MEASUREMENTS OF S/N 1, 2 AND 4 RETROREFLECTORS AT PERKIN-ELMER.

ZYGO

22 October 1974

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TASKS CARRIED OUT BY ZYGO

I. Reduced Original T-G Interferograms for 6 cube corners.

II. Remeasured Dihedral Angles.

III. Had Moore Special Tool Measure Dihedral Angles.

IV. Analyzed and Tabulated the Results of Tasks I, II and III.

ZYGO

22 October 1974

DIHEDRAL ANGLE MEASUREMENTS

Cube Corner I.D.#	Dihedral Angle	Moore (arc sec)*	Zygo (arc sec)* Operator #1	Zygo (arc sec)* Operator #2
1	R1-R2	2.14±0.02	2.10±0.02	2.05±0.03
	R3-R2	2.00±0.07	1.67±0.06	1.89±0.07
	R3-R1	1.72±0.09	1.55±0.05	1.75±0.03
2	R1-R2	1.68±0.04	1.33±0.02	1.63±0.05
	R3-R2	1.84±0.02	1.38±0.06	1.81±0.05
	R3-R1	1.76±0.05	1.38±0.03	1.76±0.04
4	R1-R2	1.82±0.02	1.68±0.05	1.46±0.03
	R3-R2	1.80±0.03	1.24±0.02	1.30±0.05
	R3-R1	1.80±0.06	1.23±0.02	1.41±0.02

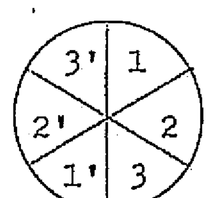
*The average angles and standard deviations above are based on five (5) measurements of each cube corner.

ZYGO

22 October 1974

ZYGO INTERFEROGRAM REDUCTION

Cube Corner I.D.#	$\Phi_{11'}$ (arc sec)	$\Phi_{22'}$ (arc sec)	$\Phi_{33'}$ (arc sec)
1	17.9	21.0	18.0
2	16.0	15.2	13.3
3	17.0	13.9	11.8
4	15.2	15.7	15.6
5	23.5	21.7	18.6
6	15.5	15.4	13.4



$\Phi_{nn'}$ = angle between the n and n' output wavefronts

ZYGO

22 October 1974

SUMMARY OF ZYGO INTERFEROGRAM REDUCTION

I.

Cube Corner I.D.#	$(\bar{\theta}_{11'} + \bar{\theta}_{22'} + {}_{33'})/3$ (arc sec)	Equivalent Average Dihedral Angle*
1	18.97	2.00
2	14.81	1.55
4	15.47	1.63

II.
Average $\bar{\theta}_{nn'}$ for all 3 Cube Corners = 16.42 arc sec.

III.
Equivalent Average Dihedral Angle = 1.73 arc sec.

* Based on $\langle\bar{\theta}_{nn'}\rangle = 4N \left(\frac{8}{3}\right)^{\frac{1}{2}}$ (Average Dihedral Angle), or where N=refractive index

$\langle\bar{\theta}_{nn'}\rangle = 9.51 \times$ (Average Dihedral Angle) for fused silica

ZYGO

22 October 1974

COMPARISON OF FFDP DATA AND ZYGO INTERFEROGRAM REDUCTION

Cube Corner I.D.#		Diameter of FFDP Centroid
1	$\bar{\Phi}_{11'}$=17.9 arc sec	22.0 arc sec
	$\bar{\Phi}_{22'}$=21.0 arc sec	
	$\Phi_{33'}$=18.0 arc sec	
2	$\bar{\Phi}_{11'}$=16.0 arc sec	19.8 arc sec
	$\bar{\Phi}_{22'}$=15.2 arc sec	
	$\bar{\Phi}_{33'}$=13.3 arc sec	
3	$\bar{\Phi}_{11'}$=17.0 arc sec	17.6 arc sec
	$\bar{\Phi}_{22'}$=13.9 arc sec	
	$\bar{\Phi}_{33'}$=11.8 arc sec	
4	$\bar{\Phi}_{11'}$=15.2 arc sec	20.6 arc sec
	$\bar{\Phi}_{22'}$=15.7 arc sec	
	$\bar{\Phi}_{33'}$=15.6 arc sec	
5	$\bar{\Phi}_{11'}$=23.5 arc sec	23.5 arc sec
	$\bar{\Phi}_{22'}$=21.7 arc sec	
	$\bar{\Phi}_{33'}$=18.6 arc sec	
6	$\bar{\Phi}_{11'}$=15.5 arc sec	18.4 arc sec
	$\bar{\Phi}_{22'}$=15.4 arc sec	
	$\bar{\Phi}_{33'}$=13.4 arc sec	

$\langle\bar{\Phi}_{nn'}\rangle$=16.58 arc sec | $\langle\Phi_{FFDP}\rangle$=20.3 arc sec

Equiv. Dih $\measuredangle$=1.74 arc sec | Equiv. Dih. $\measuredangle$=2.14 arc sec

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ZYGO

22 October 1974

DIHEDRAL ANGLE SUMMARY

(Average of 9 Dihedral Angles
for Cube Corners 1, 2 and 4)

Source	Method	Average Dihedral Angle
Itek	Interferogram Reduction	1.82±0.07
Moore	Mechanical Measurement	1.84±0.05 *
Zygo	Interferogram Reduction	1.73±0.07
Zygo	Mechanical Measurement	1.60±0.06 *

* Standard deviation based on spread of measured dihedral angles

DIHEDRAL ANGLE MEASUREMENTS

REWORKED RETROREFLECTORS

RETROREFLECTOR S/N		DIHEDRAL ANGLES* (ARC SEC)	AVG. DIHEDRAL ANGLE (ARC SEC)
1 RW	1-2	0.97	0.98 AVG.
	2-3	1.10	
	3-1	0.86	
2 RW	1-2	1.37	1.29 AVG.
	2-3	1.26	
	3-1	1.24	
3 RW	1-2	0.72	0.79 AVG.
	2-3	0.84	
	3-1	0.82	

*BASED ON AVERAGE OF FIVE (5) MECHANICAL MEASUREMENTS

ZYGO

CUBE # 1-RW DATE: 11-27-74

Uncoated Prism

1. MASTER .00 TIME:

1 - 2 +.97

3 - 2 +.87

3 - 1 +.84

2. MASTER -.06 TIME:

1 - 2 +.96

3 - 2 +1.19

3 - 1 +.99

3. MASTER -.02 TIME:

1 - 2 +.96

3 - 2 +1.18

3 - 1 +.88

4. MASTER .00 TIME:

1 - 2 +.94

3 - 2 +1.20

3 - 1 +.77

5. MASTER .00 TIME:

1 - 2 +.101

3 - 2 +1.05

3 - 1 +.83

σ = .976

Gary M VanZilene
Signature

ZYGO CUBE # 2-RW DATE: 11-27-74

Uncoated Prism

1. MASTER .00 TIME:

1 - 2 +1.37

3 - 2 +1.33

3 - 1 +1.26

2. MASTER +.05 TIME:

1 - 2 +1.33

3 - 2 +1.25

3 - 1 +1.09

3. MASTER +.07 TIME:

1 - 2 +1.41

3 - 2 +1.27

3 - 1 +1.31

4. MASTER +.10 TIME:

1 - 2 +1.40

3 - 2 +1.29

3 - 1 +1.32

5. MASTER +.05 TIME:

1 - 2 +1.33

3 - 2 +1.15

3 - 1 +1.22

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< > = 1.288

Gary M. VanZiler

Signature

ZYGO

CUBE # 3-2W DATE: 11-27-74

Uncoated Prism

1. MASTER -.02 TIME: ________

   1 - 2 +.71

   3 - 2 +.83

   3 - 1 +.85

2. MASTER .00 TIME: ________

   1 - 2 +.68

   3 - 2 +.85

   3 - 1 +.81

3. MASTER .00 TIME: ________

   1 - 2 +.75

   3 - 2 +.89

   3 - 1 +.85

4. MASTER .00 TIME: ________

   1 - 2 +.72

   3 - 2 +.83

   3 - 1 +.74

5. MASTER .00 TIME: ________

   1 - 2 +.75

   3 - 2 +.79

   3 - 1 +.83

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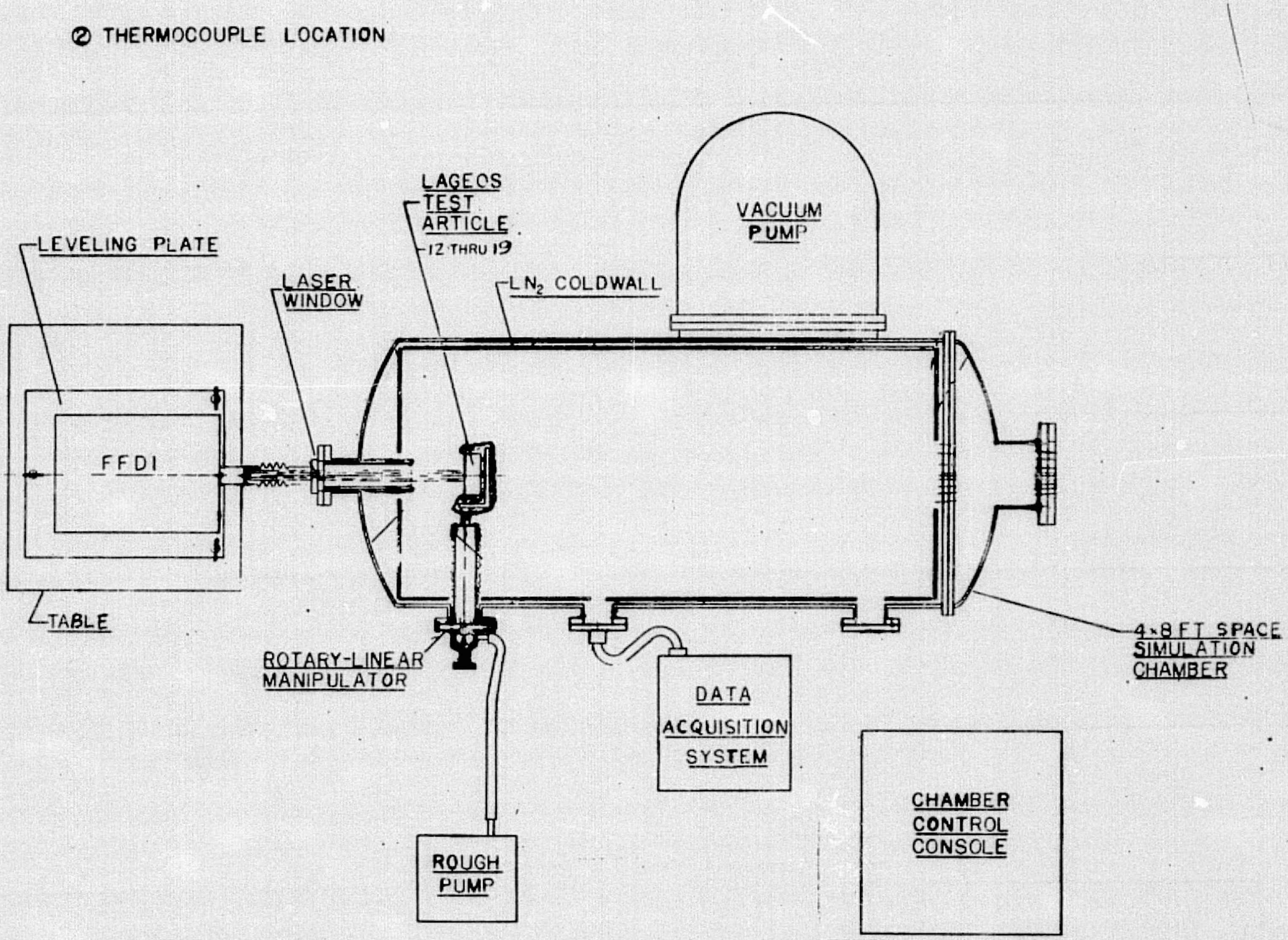
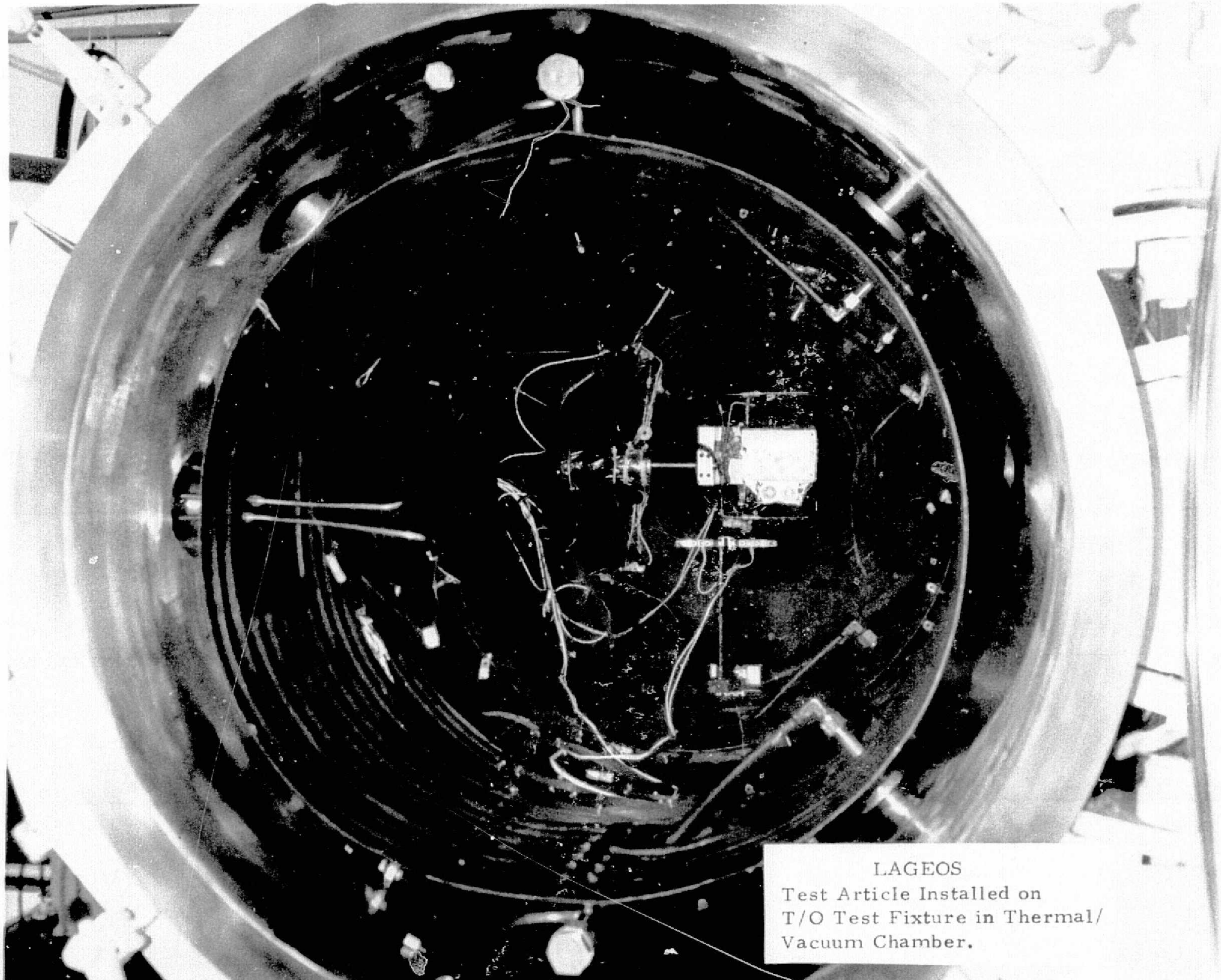
$\langle\ \rangle = .79$

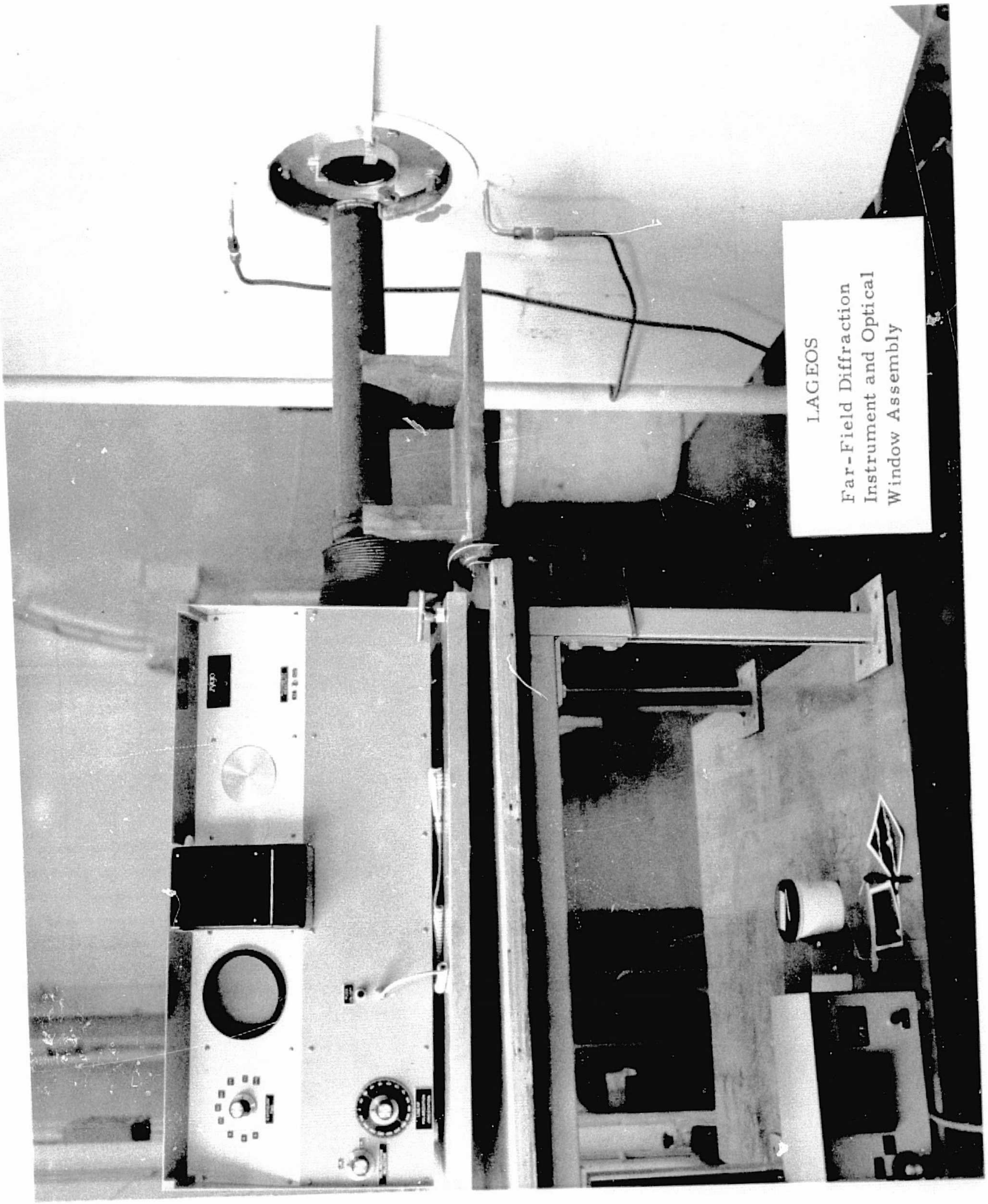
Gary M. VanZilen
Signature

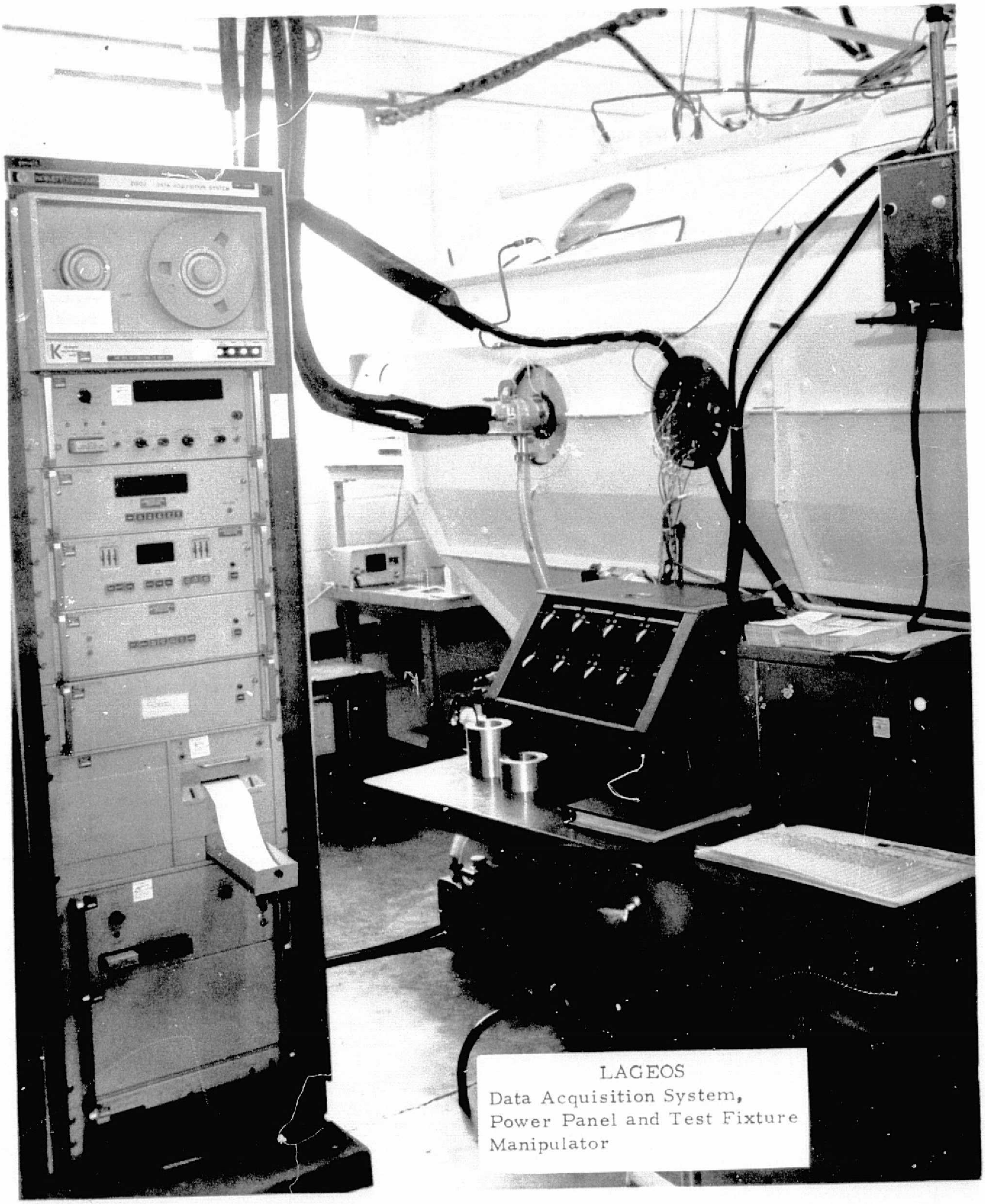


LAGEOS TEST SETUP - THERMAL-VACUUM



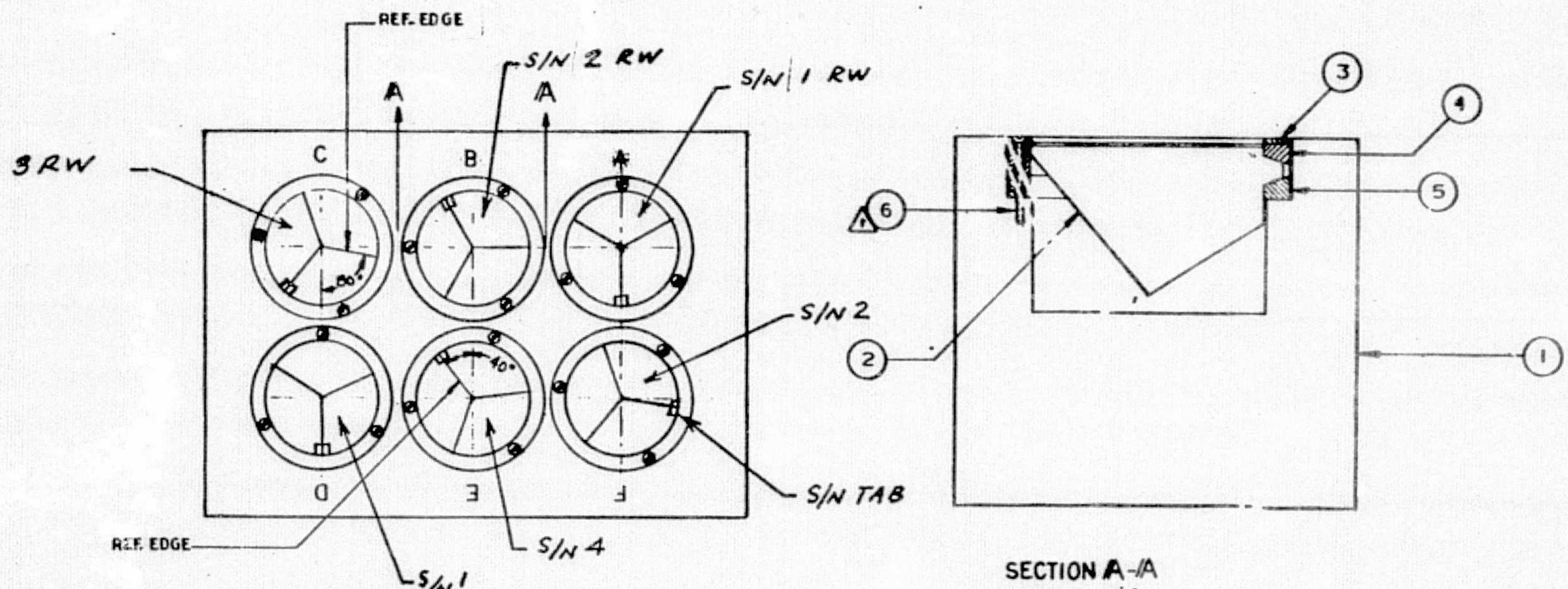
LAGEOS
Test Article Installed on
T/O Test Fixture in Thermal/
Vacuum Chamber.


LAGEOS
Far-Field Diffraction
Instrument and Optical
Window Assembly



LAGEOS
Data Acquisition System, Power Panel and Test Fixture Manipulator

NOTES:
⚠1 TORQUE ITEM 6 TO 1.4$^{+.0}_{-.2}$ IN-LBS.
⚠2 CLEAN, HANDLE AND ASSEMBLE IN ACCORDANCE WITH 2374465



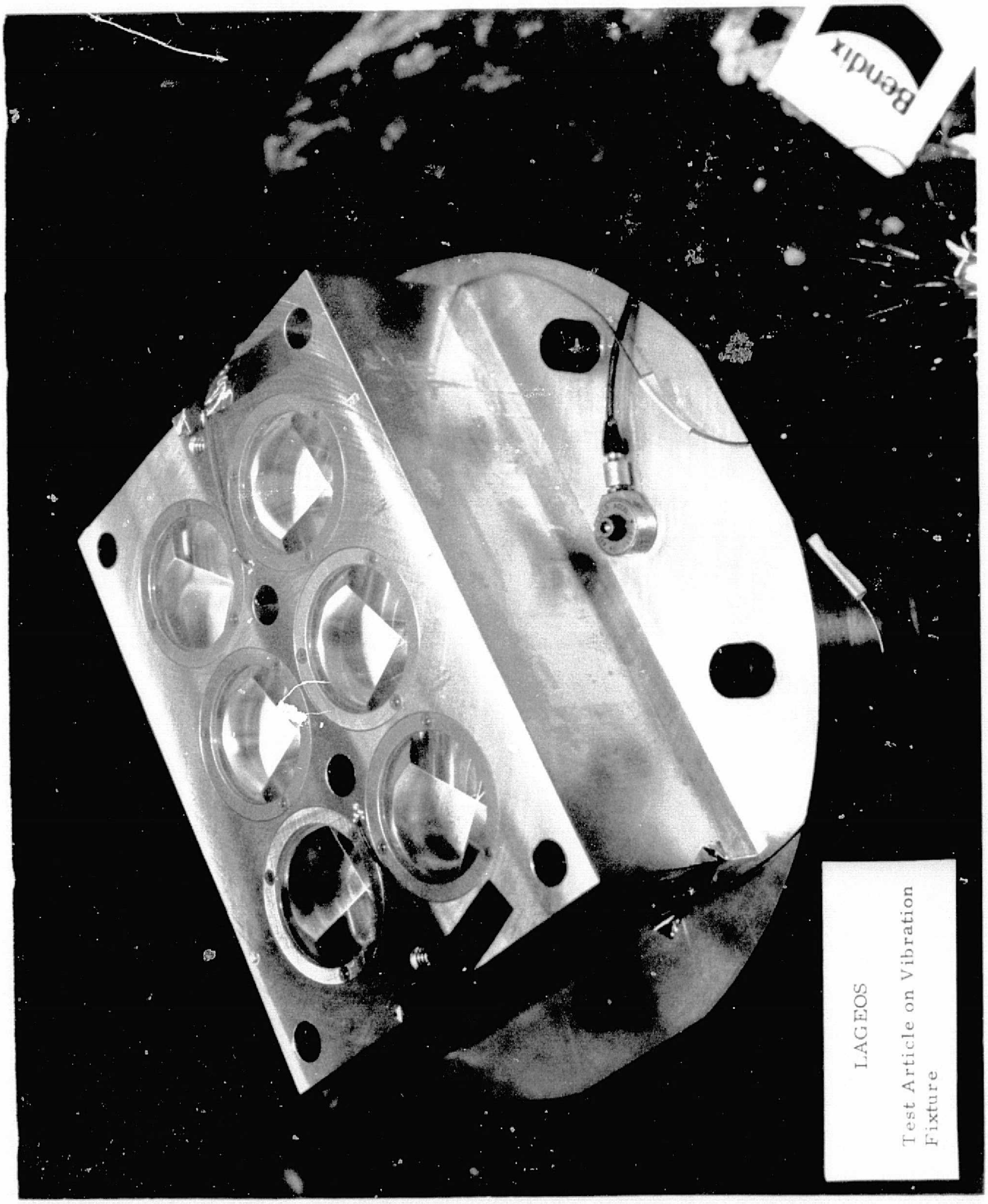
SECTION A-A
SCALE 2/1

RETROREFLECTORS	
S/N	DESCRIPTION
1	9118-1001 (ORIGINAL)
2	9118-1001 (ORIGINAL)
1 RW	9118-1001 (REWORKED)
4	9118-1001 (ORIGINAL)
2 RW	9118-1001 (REWORKED)
3 RW	100-2664-001 (REWORKED)

QTY REQD	DESCRIPTION	CODE IDENT	PART OR SPECIFICATION NO.	ITEM
⚠1 13	SCREW		MS35202-[illegible]	6
6	LOWER RING		2374462	5
6	UPPER RING		2374461	4
6	RETAINER RING		2374463	3
6	RETRO		AS NOTED	2
1	PANEL		2374464	1

LIST OF MATERIALS

LAGEOS TEST ARTICLE
ASSEMBLY



LAGEOS

Test Article on Vibration Fixture

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18 December 1974

SUMMARY - OPTICAL TEST RESULTS

RETROREFLECTOR S/N	AVG. DIHEDRAL ANGLE (ARC SEC)	ANNULAR-TO-FULL FIELD RATIO ISOTHERMAL-VACUUM	ISOTHERMAL-AMBIENT
1 RW	0.98 *	0.14	0.14
2 RW	1.29 *	0.16	0.15
3 RW	0.79 *	0.13	0.12
1	1.74 **	0.094 (.088)	0.10 (.098)
2	1.90 **	0.083 (.088)	0.091 (.084)
4	1.82 **	0.099 (.089)	0.11 (.11)

* BASED ON ZYGO MECHANICAL MEASUREMENTS

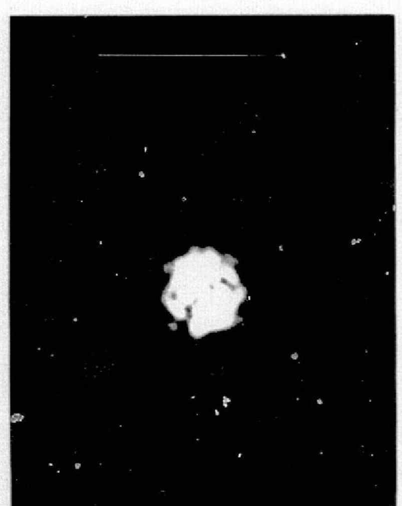
** BASED ON ITEK INTERFEROGRAM ANALYSIS

( ) DATA FROM EARLIER TESTS

FAR-FIELD DIFFRACTION PATTERN TEST RESULTS

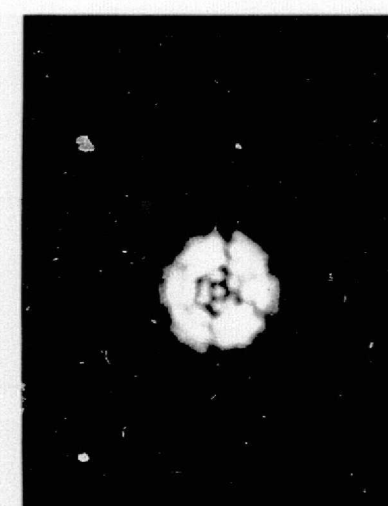
Isothermal-Vacuum Conditions
Normal Laser Incident Angles
Exposure Time: 1/250 sec
Test Dates Noted

S/N 3 RW
12/5/74



S/N 1 RW
12/5/74

S/N 2 RW
12/5/74



S/N 4
12/6/74

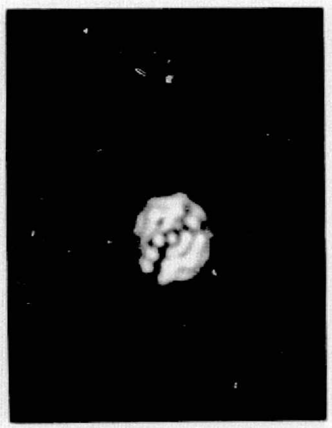
FAR-FIELD DIFFRACTION PATTERN COMPARSIONS

- Isothermal-Ambient Conditions
  - Normal Laser Incident Angle
- Test Dates Noted
  - Exposure Time: 1/250 sec.

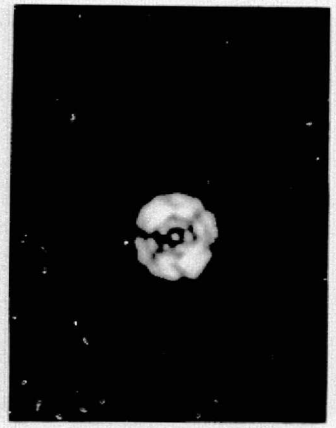
S/N 3 RW
12/10/74

S/N 1 RW
12/10/74

S/N 2 RW
12/10/74



S/N 3
8/16/74



S/N 6
8/16/74

S/N 4
12/9/74

S/N 1
12/9/74

S/N 2
12/9/74

S/N 5
8/16/74

BASELINE TEST RESULTS COMPARISONS

- Far-Field Diffraction Patterns
- Isothermal-Vacuum Conditions
- Normal Laser Incident Angles
- Test Dates Noted

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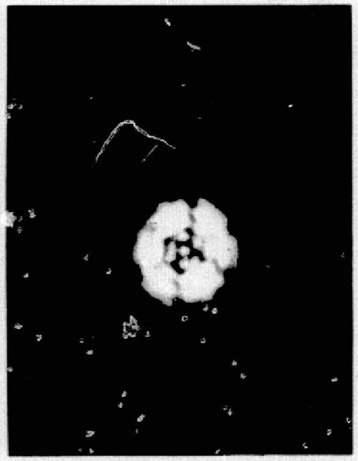
A-19

S/N 1
12/6/74



A-20

S/N 4
12/6/74

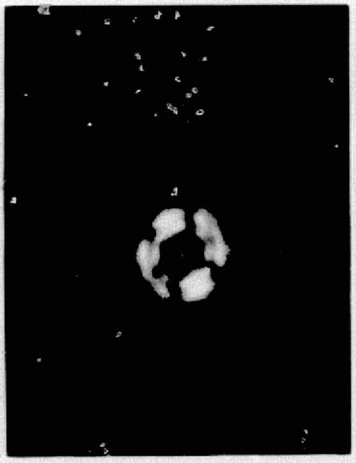
A-21

S/N 2
12/6/74

#159

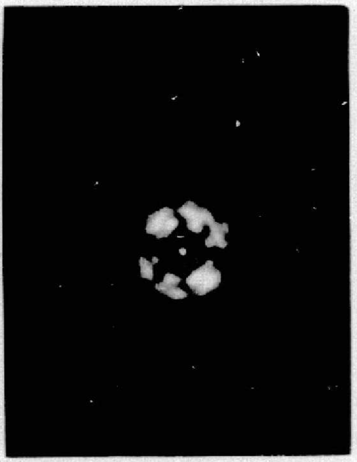
S/N 1
8/12/74

#164



S/N 4
8/12/74

#169

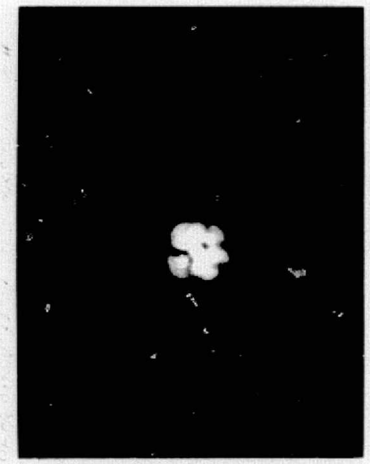


S/N 2
8/12/74

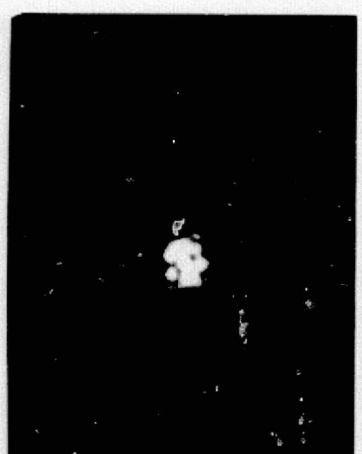
COMPARISON OF RETROREFLECTOR TYPES

- Isothermal-Ambient Conditions
- Normal Laser Incident Angles
- Test Date Noted

Zygo Master Cube
Exposure Time: 1/500 sec.
12/4/74

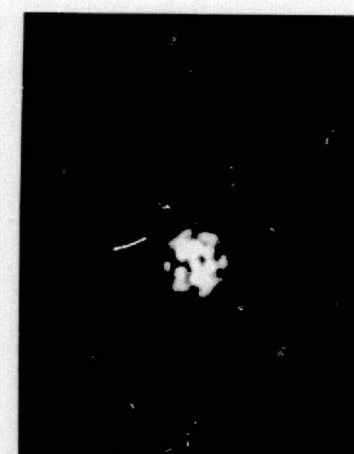


Apollo S/N 415-A
Exposure Time: 1/500 sec
10/22/74



S/N 3 RW
Exposure Time: 1/500 sec
12/10/74

S/N 1 RW
Exposure Time: 1/500 sec
12/10/74



S/N 2 RW
Exposure Time: 1/500 sec
12/10/74

SUMMARY OPTICAL TEST RESULTS

RETROREFLECTOR S/N	AVG. DIHEDRAL ANGLE (ARC SEC)	FAR-FIELD DIFFRACTION PATTERN ENERGY CENTROID DIAMETER (ARC SEC) *
1 RW	0.98	13.2
2 RW	1.29	14.7
3 RW	0.79	12.5

* BASED ON ZYGO MECHANICAL MEASUREMENTS

* BASED ON FFDI PHOTO DATA

CONCLUSIONS AND RECOMMENDATIONS

- BASED ON OPTICAL TEST RESULTS, 16% RELATIVE ENERGY IN THE LAGEOS ANNULUS CAN BE ACHIEVED WITH THE LAGEOS RETROREFLECTOR.

- THE REWORKED RETROREFLECTORS HAVE PROVIDED DATA POINTS ON THE DECREASING ENERGY PORTION OF THE OPTIMIZATION CURVE.

- THE OFF-SET BETWEEN THE MECHANICALLY-DETERMINED DIHEDRAL ANGLES AND THE INTERFEROMETRICALLY-DETERMINED ANGLES FOR THE REWORKED RETRO-REFLECTORS MAKES DETERMINATION OF THE OPTIMUM DIHEDRAL ANGLE (BASED ON MAXIMUM RELATIVE ENERGY) DIFFICULT.

- IT IS RECOMMENDED THAT RELATIVE ENERGY IN THE FAR-FIELD DIFFRACTION PATTERN ANNULUS BE USED AS A RETROREFLECTOR ACCEPTANCE CRITERIA FOR LAGEOS AND THAT DIHEDRAL ANGLES BE SPECIFIED AS A REFERENCE DIMENSION ONLY. THE TEST RESULTS MAY BE USED TO SELECT THE MINIMUM ACCEPTABLE PERFORMANCE.

- FURTHER INVESTIGATION INTO THE REASONS FOR THE NEARLY CONSTANT OFF-SET BETWEEN MECHANICAL MEASUREMENTS AND INTERFEROMETRIC MEASUREMENTS OF DIHEDRAL ANGLES IS RECOMMENDED. THE DIRECTION OF THIS INVESTIGATION TO BE DETERMINED JOINTLY BETWEEN NASA/MSFC, BENDIX, ITEK AND ZYGO.

LAGEOS

DIHEDRAL ANGLE IMPROVEMENT PROGRAM

PREPARED UNDER

CONTRACT TO

BENDIX AEROSPACE SYSTEMS DIVISION

18 DECEMBER 1974

Itek

PURPOSE/OBJECTIVES

RESOLVE CONTRADICTIONS IN TEST RESULTS

- PREDICT DIHEDRAL ANGLES FROM INTERFEROGRAMS

  COMPARE WITH INDEPENDENT MEASUREMENTS
- PREDICT FAR FIELD PATTERN FROM INTERFEROGRAMS

  COMPARE WITH MEASURED DATA
- RECOMMEND REVISED DIHEDRAL ANGLE
- ANALYZE REWORKED CUBES

TASKS

- EVALUATE EXISTING CUBES
  - ANALYZE ZYGO INTERFEROGRAMS
    - PREDICT DIHEDRAL ANGLES
  - TEST CUBES IN TWYMAN-GREEN INTERFEROMETER
  - ANALYZE ITEK INTERFEROGRAMS
    - PREDICT DIHEDRAL ANGLES
    - PREDICT FAR FIELD PATTERN
- TOLERANCE ANALYSIS (.9 - 2.1 ARC-SEC)
- MODEL COMPARISON (SAO)
- EVALUATE REWORKED CUBES
  - ANALYZE ZYGO INTERFEROGRAMS
    - PREDICT DIHEDRAL ANGLES
    - PREDICT FAR FIELD PATTERN

SUMMARY - DIHEDRAL ANGLE

		AVERAGE DIHEDRAL ANGLE (ARC-SEC)
***	ITEK INTERFEROGRAMS	1.77
***	ZYGO INTERFEROGRAMS	1.86
*	ITEK FFDP	1.98
**	BENDIX FFDP	2.14

*Based on far field pattern predicted from interferograms.
**Based on far field pattern photograph measurement.
***Analyzed by Itek.

SUMMARY - FAR FIELD DIFFRACTION PATTERN

	AVERAGE PERCENT ENERGY IN 13.2 - 16.9 ARC-SEC ANNULUS	AVERAGE CENTROID DIAMETER (ARC-SEC)
ITEK INTERFEROGRAM	14.3	18.7
BENDIX MEASUREMENT	9.7	20.3

SUMMARY - TOLERANCE STUDY

- PERCENT ENERGY IN 13.2 - 16.9 ARC-SEC ANNULUS VARIES FROM 13.0 TO 18.5 FOR DIHEDRAL ANGLES OF .9-2.1 ARC-SEC
- PEAK PERCENT ENERGY OCCURS AT ABOUT 1.35 ARC-SEC DIHEDRAL ANGLE.
- CENTROID DIAMETER VARIES FROM 12.4 TO 22.0 ARC-SEC FOR DIHEDRAL ANGLES OF .9 - 2.1 ARC-SEC.
- OFF-NOMINAL CUBE (.0, +.5, -.5 ARC-SEC ERRORS) INCREASES CENTROID DIAMETER BY UP TO 1.0 ARC-SEC AND CHANGES PERCENT ENERGY BY UP TO 0.7.

COMPARISON OF DIHEDRAL ANGLES ON CUBES
1, 2, AND 4

Cube	*Itek Interferograms			*Zygo Interferograms			Moore Mechanical Measurements		
1	1.51	1.76	1.95	2.44	1.84	2.04	2.14	2.00	1.72
2	1.68	2.03	1.98	1.98	1.76	0.98	1.68	1.84	1.76
4	1.85	1.75	1.85	2.02	1.31	1.65	1.82	1.80	1.80
Average	1.82			1.78			1.84		

*Analyzed by Itek.

COMPARISON OF AVERAGE DIHEDRAL ANGLE (arc-sec)

Cube	*** Itek Interferogram	*** Zygo Interferogram	*Itek FFDP	**Bendix FFDP
1	1.74	2.11	1.96	2.32
2	1.90	1.57	2.13	2.08
3	1.44	1.78	1.74	1.85
4	1.82	1.66	1.96	2.17
5	2.14	2.31	2.30	2.48
6	1.59	1.71	1.78	1.94
Average	1.77	1.86	1.98	2.14

*Based on far field pattern predicted from interferograms.
**Based on far field pattern photograph measurement.
***Analyzed by Itek.

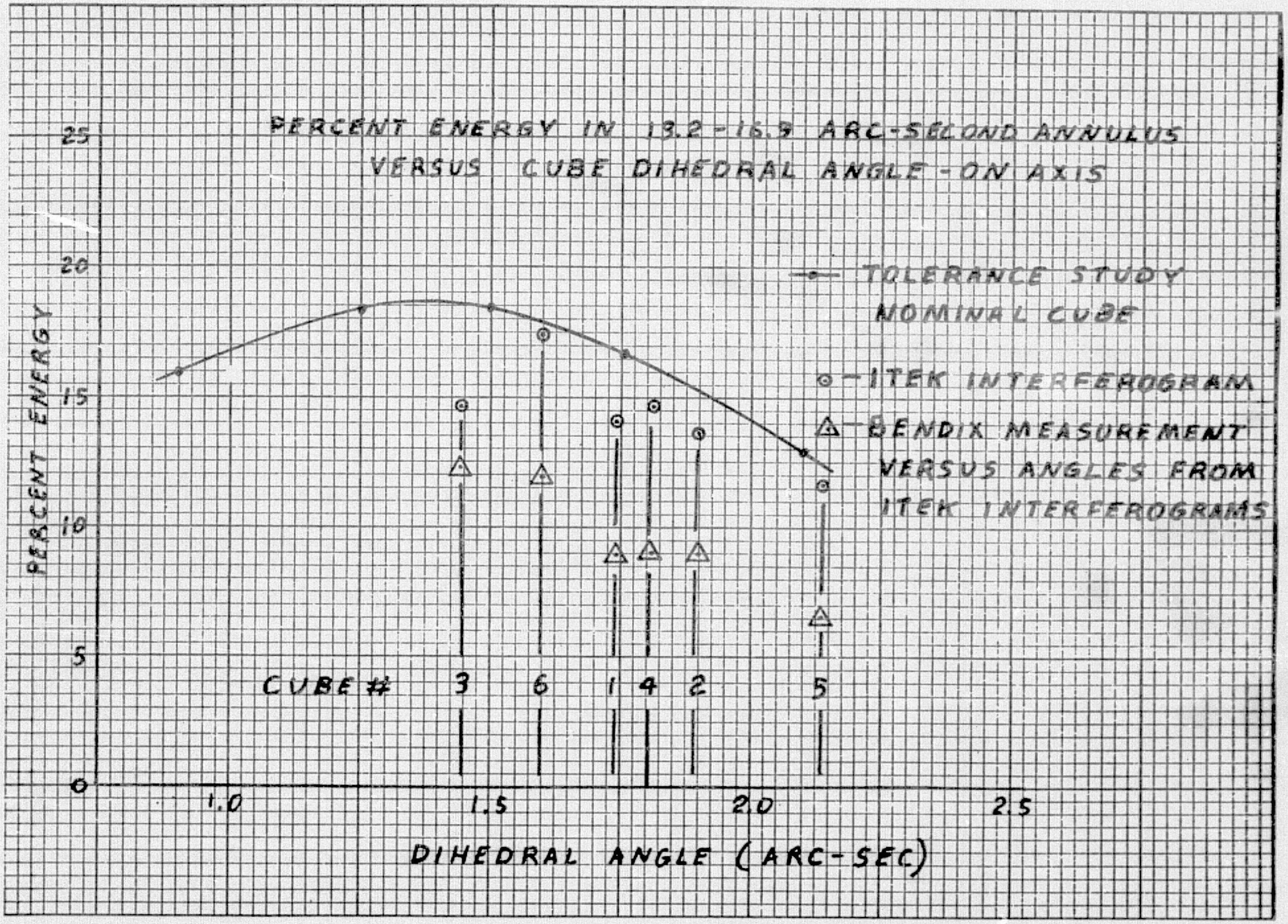
FAR FIELD CHARACTERISTICS OF LAGEOS RETROREFLECTOR - ON-AXIS

Cube #	Percent Energy 13.2 - 16.9 Arc-Sec Itek Interferogram	Percent Energy 13.2 - 16.9 Arc-Sec Bendix Measurement	Centroid Diameter (Arc-Sec) Itek Interferogram	Centroid Diameter (Arc-Sec) Bendix Measurement
1	14.0	8.9	18.6	22.0
2	13.6	8.9	20.2	19.8
3	14.7	12.4	16.4	17.6
4	14.6	9.0	18.6	20.6
5	11.7	6.7	21.9	23.5
6	17.4	12.0	16.6	18.4
Average	14.3	9.7	18.7	20.3

TOLERANCE STUDY
Encircled Energy & Apparent
Centroid Diameter
On-Axis

Case	Percent Energy 13.2 - 16.9 Arc-Sec	Apparent Centroid Diameter (Arc-Sec)
0.9 Arc-Sec Nominal Cube	16.0	12.4
* 0.9 Arc-Sec Off Nominal Cube	16.7	13.4
1.25 Arc-Sec Nominal Cube	18.3	14.4
1.5 Arc-Sec Nominal Cube	18.5	16.5
* 1.5 Arc-Sec Off Nominal Cube	18.2	17.3
1.75 Arc-Sec Nominal Cube	16.8	18.6
2.1 Arc-Sec Nominal Cube	13.0	22.0
* 2.1 Arc-Sec Off Nominal Cube	12.3	22.4

*.0, +.5, -.5 Arc-Sec Errors


PERCENT ENERGY IN 13.2 - 16.9 ARC-SECOND ANNULUS
VERSUS CUBE DIHEDRAL ANGLE - ON AXIS
TOLERANCE STUDY NOMINAL CUBE
ITEK INTERFEROGRAM
BENDIX MEASUREMENT VERSUS ANGLES FROM ITEK INTERFEROGRAMS
PERCENT ENERGY
0
5
10
15
20
25
CUBE #
3
6
1
4
2
5
1.0
1.5
2.0
2.5
DIHEDRAL ANGLE (ARC-SEC)

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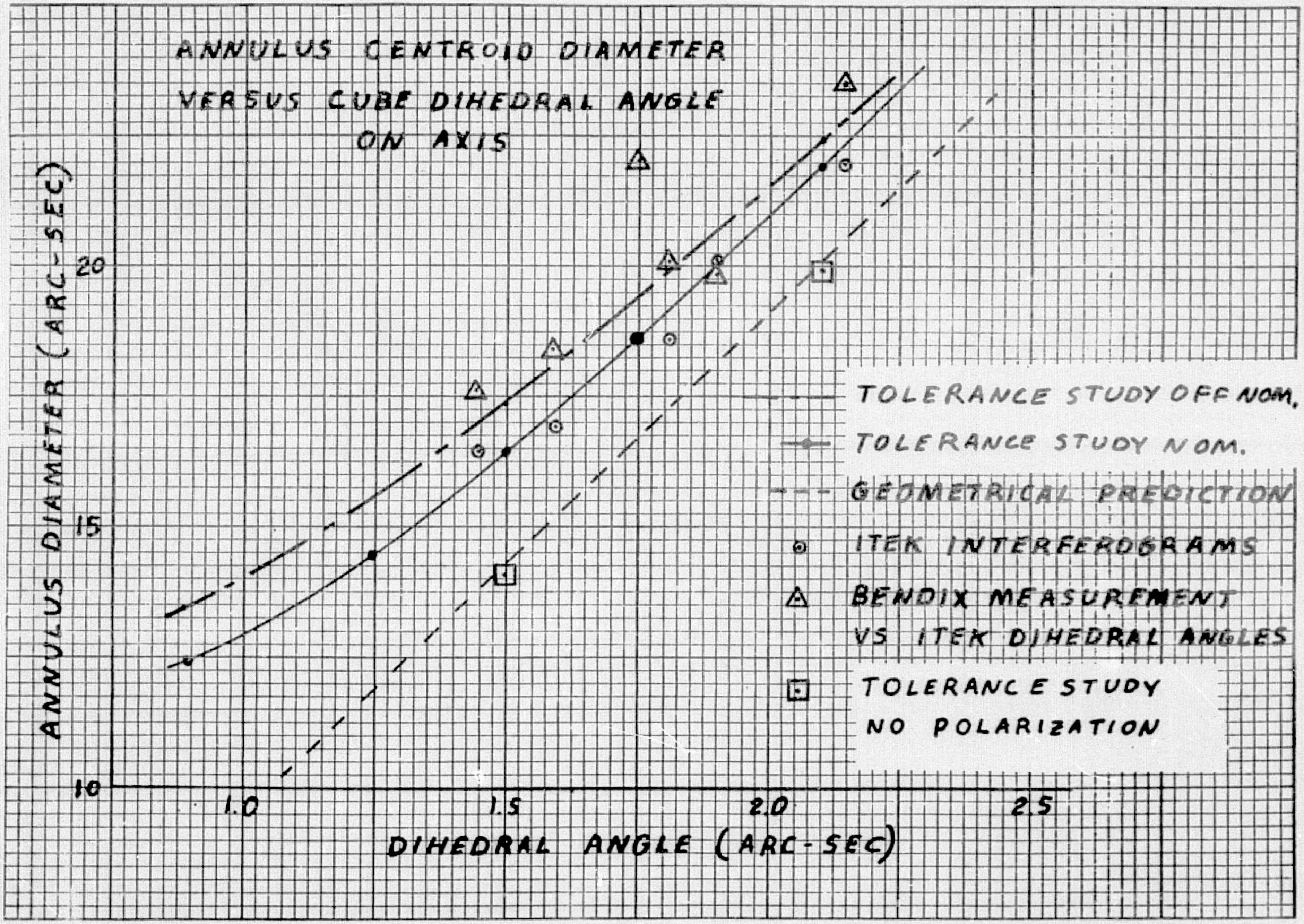


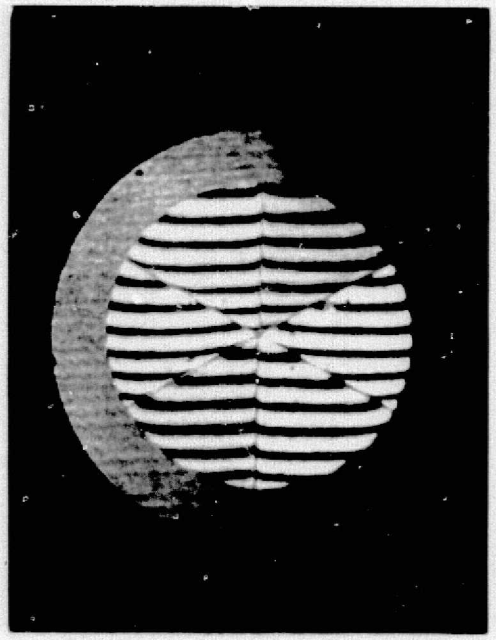
SUMMARY

- AVERAGE DIHEDRAL ANGLE IS 1.8 ARC-SEC.
- AVERAGE FAR FIELD CENTROID DIAMETER IS 18.0 ARC-SEC.
- PEAK ENERGY IN 13.2 - 16.9 ARC-SEC CENTROID OCCURS FOR A 1.35 ARC-SEC CUBE.
- .0 + .5, -.5 ARC-SEC ERRORS INCREASE CENTROID DIAMETER SLIGHTLY.
- MEASURED FFDP SHOWS HIGH CENTROID DIAMETER AND LOW PERCENT ENERGY IN 13.2 - 16.9 ARC-SEC ANNULUS.

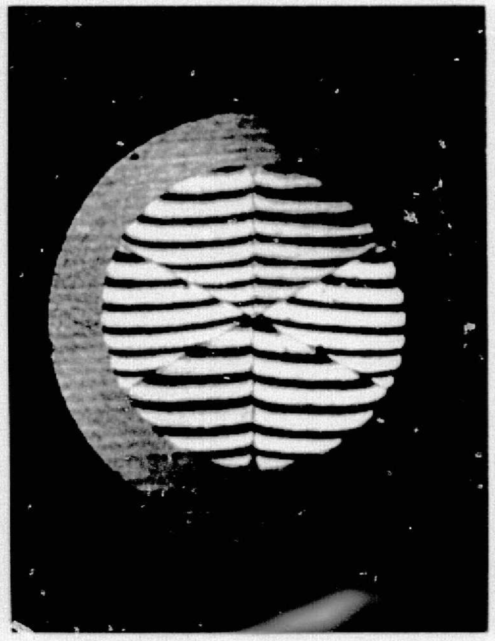
PRELIMINARY CONCLUSIONS/RECOMMENDATIONS

- INTERFEROMETRIC MEASUREMENT OF DIHEDRAL ANGLES AGREES WITH MECHANICAL MEASUREMENTS ON THE AVERAGE
- PREDICTED FFDP DIFFRACTION PATTERNS AGREE WITH MEASURED PATTERNS CLOSER THAN PREVIOUS PREDICTIONS
- FAR FIELD ANNULUS IS LARGER THAN GEOMETRICAL PREDICTION DUE TO DIFFRACTION/POLARIZATION
- NOMINAL DIHEDRAL ANGLES SHOULD BE REDUCED TO APPROXIMATELY 1.25 ARC-SEC.
- ANALYZE AND TEST REWORKED CUBES AS PLANNED
- CONSIDER ANALYSIS FOR OTHER INCIDENT ANGLES AND WAVE LENGTHS

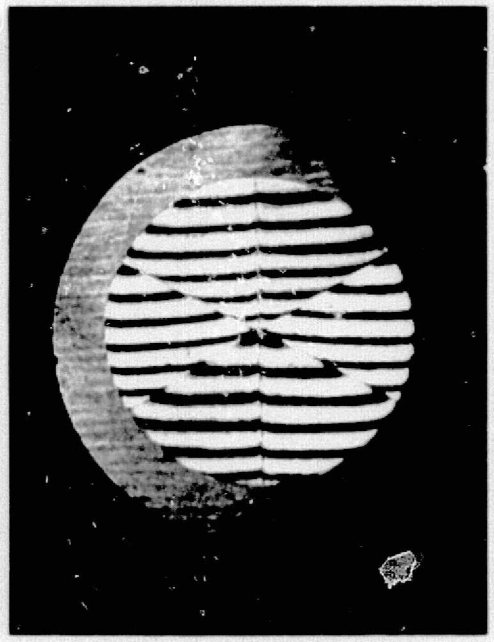
INTERFEROGRAMS OF REWORKED CUBES



1 RW



#2 RW



#3 RW

INTERFEROMETRIC MEASUREMENT OF DIHEDRAL ANGLES ON REWORKED CUBES (ARC-SEC)

REWORKED CUBE	INTERFEROGRAM 1	2	3	AVERAGE	AVE.
1	.73 .30 .45	.79 .38 .33	.83 .28 .30	.78 .32 .36	.49
2	.67 .89 .77	.58 .91 .73	.91 .79 .59	.72 .86 .70	.76
3	.28 .17 .40	.24 .30 .16	.25 .26 .30	.26 .24 .29	.26

* BASED ON INTERFEROGRAM PRODUCED BY ZYGO AND ANALYZED BY ITEK

COMPARISON OF DIHEDRAL ANGLES ON REWORKED CUBES (ARC-SEC)

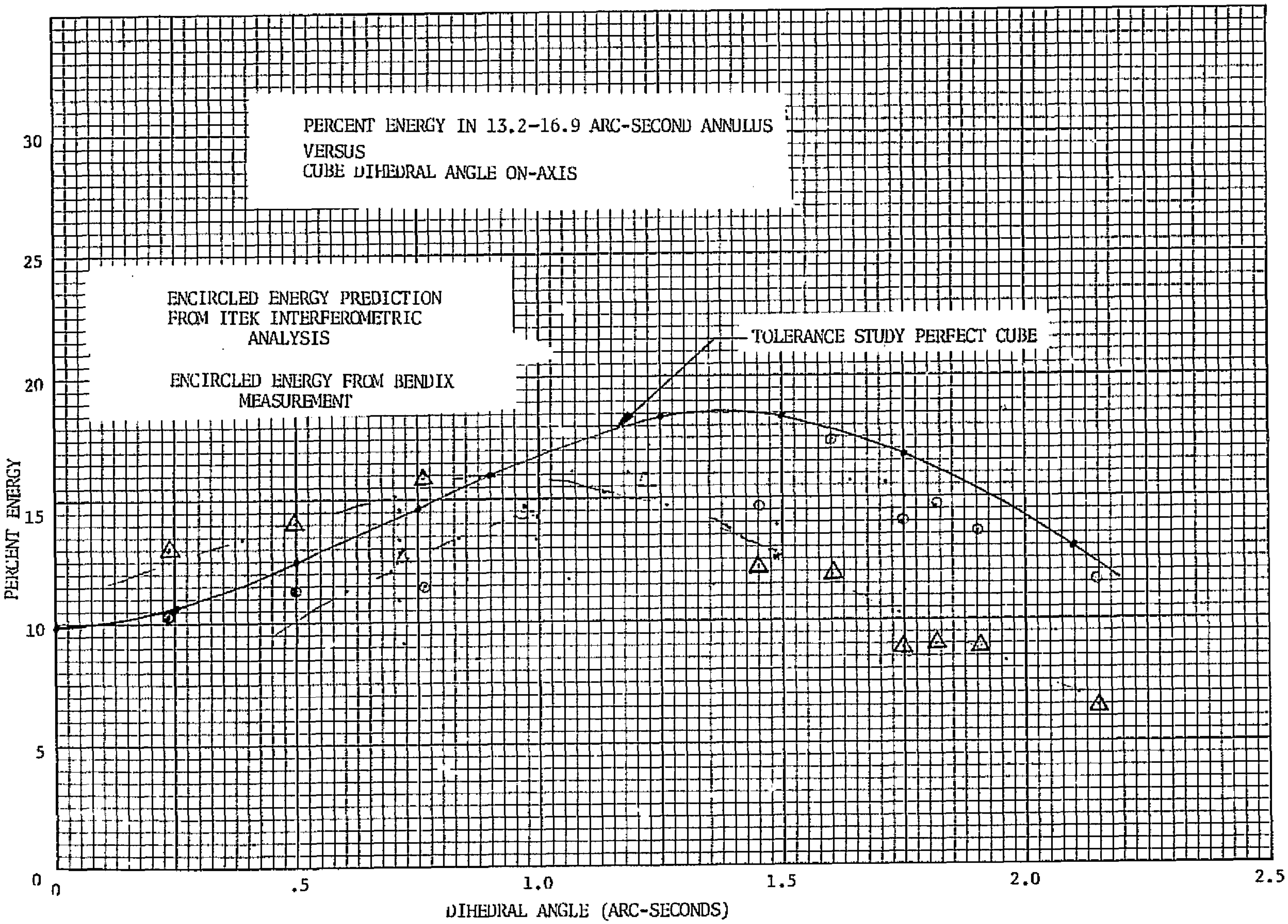
REWORKED CUBE	ITEK INTERFEROGRAM *	AVE.	ZYGO MECHANICAL MEASUREMENT	AVE.	DIFFERENCE
1.	0.78 0.32 0.36	0.49	0.97 1.10 0.86	0.98	0.49
2	0.72 0.86 0.70	0.76	1.37 1.26 1.24	1.29	0.53
3	0.26 0.24 0.29	0.26	0.72 0.84 0.82	0.79	0.55

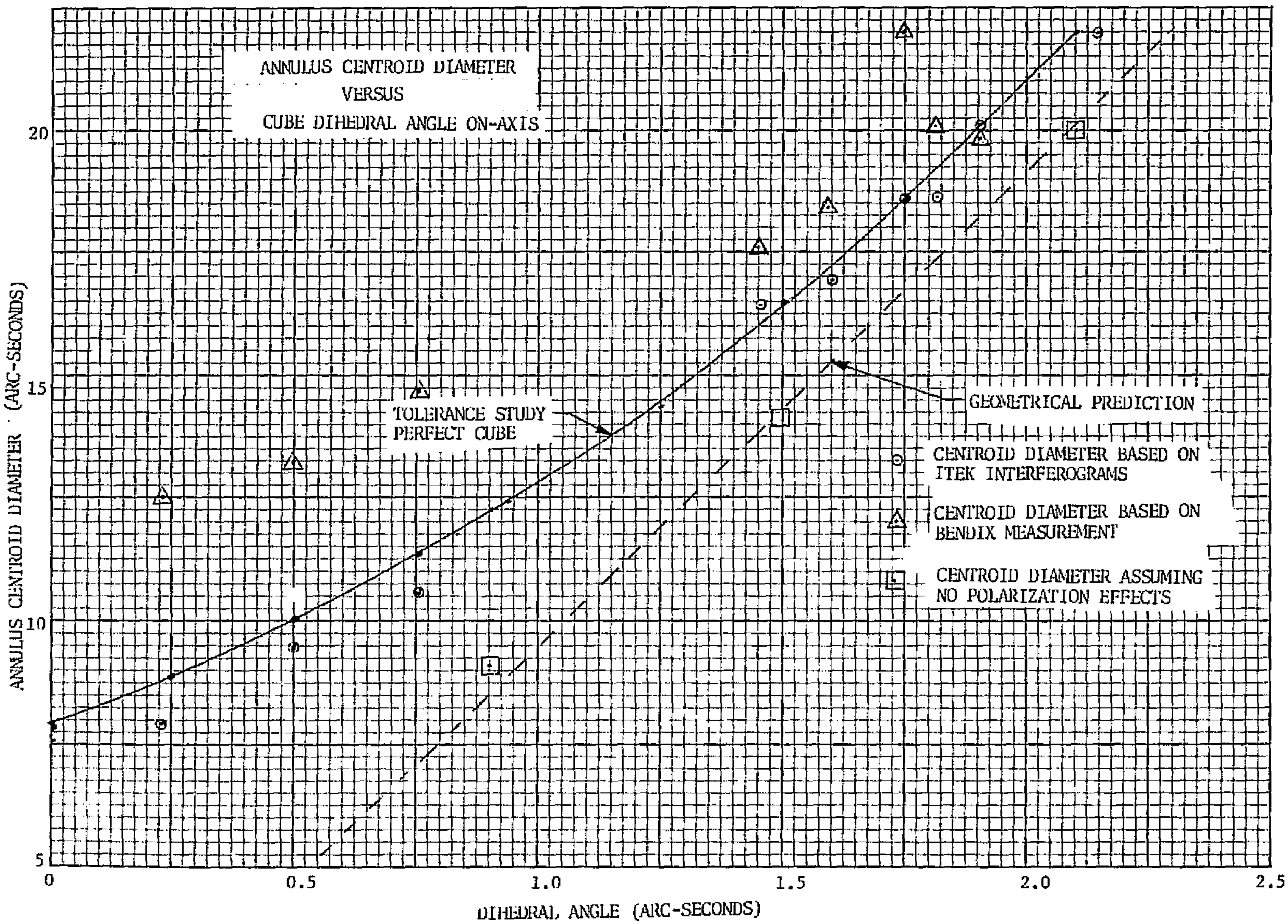
* BASED ON INTERFEROGRAM PRODUCED BY ZYGO AND ANALYZED BY ITEK

FAR FIELD CHARACTERISTICS OF REWORKED CUBES ON AXIS

REWORKED CUBE	PERCENT ENERGY 13.2 - 16.9 ARC SEC		CENTROID DIAMETER (ARC- SEC)	
	ITEK INTERFEROGRAM	BENDIX MEASUREMENT	ITEK INTERFEROGRAM	BENDIX MEASURED
1	11.35	14.0	9.4	13.2
2	11.5	16.0	10.5	14.7
3	10.4	13.0	7.9	12.5

* BASED ON INTERFEROGRAM PRODUCED BY ZYGO AND ANALYZED BY ITEK


PERCENT ENERGY IN 13.2-16.9 ARC-SECOND ANNULUS
VERSUS
CUBE DIHEDRAL ANGLE ON-AXIS
ENCIRCLED ENERGY PREDICTION
FROM ITEK INTERFEROMETRIC
ANALYSIS
ENCIRCLED ENERGY FROM BENDIX
MEASUREMENT
TOLERANCE STUDY PERFECT CUBE
PERCENT ENERGY
30
25
20
15
10
5
0
0
.5
1.0
1.5
2.0
2.5
DIHEDRAL ANGLE (ARC-SECONDS)


ANNULUS CENTROID DIAMETER
VERSUS
CUBE DIHEDRAL ANGLE ON-AXIS
TOLERANCE STUDY
PERFECT CUBE
GEOMETRICAL PREDICTION
CENTROID DIAMETER BASED ON
ITEK INTERFEROGRAMS
CENTROID DIAMETER BASED ON
BENDIX MEASUREMENT
CENTROID DIAMETER ASSUMING
NO POLARIZATION EFFECTS
ANNULUS CENTROID DIAMETER (ARC-SECONDS)
20
15
10
5
0
0.5
1.0
1.5
2.0
2.5
DIHEDRAL ANGLE (ARC-SECONDS)

MODEL COMPARISON (SAO)

- DISCREPANCIES IN FAR FIELD INTENSITY OF UP TO 10 PERCENT OF PEAK INTENSITY BETWEEN ITEK AND SAO MODEL
- MODIFICATIONS WERE MADE TO ITEK MODEL
- AGREEMENT WITH SAO MODEL OBTAINED
- EFFECT ON RESULTS LESS THAN 0.1% OF TOTAL ENERGY IN 13.2 - 16.9 ARC-SECOND ANNULUS

SUMMARY

- INTERFEROMETRICALLY PREDICTED DIHEDRAL ANGLES ON REWORKED CUBES SMALLER THAN THE DESIRED ANGLES BY ABOUT 0.5 ARC-SECOND
- MECHANICAL MEASUREMENTS OF DIHEDRAL ANGLES ON REWORKED CUBES ARE 0.5 ARC-SECOND LARGER THAN INTERFEROMETRIC PREDICTIONS
- MEASURED FFDP FOR <u>REWORKED CUBES</u> HAS HIGHER PERCENT ENERGY IN ANNULUS THAN INTERFEROMETRIC PREDICTIONS
- INTERFEROMETRICALLY PREDICTED CENTROID DIAMETER FOR REWORKED CUBES IS SMALLER THAN BENDIX MEASUREMENT
- EFFECT OF DISCREPANCIES WITH SAO RESULT IN DEVIATIONS LESS THAN 0.1% IN 13.2-16.9 ARC-SECONDS ANNULUS

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CONCLUSIONS/RECOMMENDATIONS

- MEASURED FFDP HAS HIGHER PERCENT ENERGY IN ANNULUS AT LOWER DIHEDRAL ANGLES AND LOWER PERCENT ENERGY AT HIGHER DIHEDRAL ANGLES THAN INTERFEROMETRIC PREDICTIONS
  - DIFFERENCES COULD BE CAUSED BY A REDUCED ANNULUS DIAMETER
- MECHANICALLY MEASURED DIHEDRAL ANGLES FOR THE REWORKED CUBES HAVE A CONSTANT OFFSET FROM THE INTERFEROMETRICALLY PREDICTED DIHEDRAL ANGLES
- BASED ON INTERFEROMETRIC ANALYSIS DIHEDRAL ANGLES SHOULD BE 1.25 ± 0.5 ARC-SECONDS.
- PRODUCTION CUBES SHOULD BE CHECKED INTERFEROMETRICALLY TO VERIFY DIHEDRAL ANGLES.

RELIABILITY		REVISIONS			CONFIG MGT
APPD	PREDICTION	LTR	DESCRIPTION	DATE	APPV'D
		X1	EXPERIMENTAL RELEASE ER-1922-20	11/26/74	L. D.

APPENDIX C

TABLE OF CONTENTS

DRAWING AND PART APPLICATION			
PART NO	NEXT ASSY	END ITEM NO.	EFFECTIVITY
2374470	N/A	N/A	N/A

CONTR NO. NAS8-30658		
PREP.	[illegible]	11-25-74
CHECKED		
TEST		
QUAL CONT		
ENGR	[illegible]	11-25-74
SYS SPT	[illegible]	11-25-74

THE BENDIX CORPORATION
AEROSPACE SYSTEMS DIVISION – ANN ARBOR, MICHIGAN

TITLE
LAGEOS Retroreflector Performance Improvement – Thermal-Optical Test Procedure

SIZE	CODE IDENT NO.	DRAWING NUMBER	REV
A	07038	TP 2374470	X1
SCALE	WEIGHT	SHEET 1 of 19	

DRAWING CLASS
A ☐ B ☐ C ☒

A 640

1.0 PURPOSE

The purpose of this test is to verify the predicted optical performance improvement expected from a change in the LAGEOS retroreflector dihedral angle. Optical performance data will be obtained for three reworked retroreflectors (LAGEOS S/N 3 and 5, and ALSEP S/N PE161A, which replaces LAGEOS S/N 6, damaged in rework) and three original retroreflectors (LAGEOS S/N 1, 2 and 4).

2.0 SCOPE

This document specifies the procedures and equipment necessary to perform the retroreflector optical tests. A series of test sequences will be performed for three original and three reworked retroreflectors under varied conditions of atmospheric pressure and vacuum at ambient temperature, while observing, photographing and measuring the return beam intensity of retroreflector far field diffraction patterns.

3.0 APPLICABLE DOCUMENTS

TP2374455	LAGEOS Phase B Thermal-Optical As-Built Test Procedure
2374458	LAGEOS T/O/V Test Article
STM 1036	Operating Procedure for NRC 4 x 8 Vacuum Chamber
--------	Operating Manual for Zygo Far Field Diffraction Instrument

4.0 PARTICIPANTS

LAGEOS Engineering Representative
Environmental/Quality Test Conductor
E/QT Thermal-Vacuum Engineer

5.0 EQUIPMENT REQUIRED

Item	Manufacturer	Part No. or Model	*Serial No.	*Calib. Date
4 x 8 Chamber	NRC	N/A	BSD 9894	N/A
Roughing Pump	N/A	N/A	N/A	N/A
FFDI	Zygo	——	17219	N/A
Fixture	BxA	2374460	N/A	N/A
Window Feedthru	BxA	2374453	N/A	N/A
Leveling Plate	BxA	2374454	N/A	N/A
Vacuum Gage	NRC	751	50627	6-4-75
Alignment Target	BxA	N/A	N/A	N/A
Data Acquisition System	HP	2010J	14329	12-27-74
Reference Oven	RI Controls	RJ4081	13722	5/22/75

*To be completed prior to testing. Equipment substitutions and additions shall be listed above.

6.0 TEST SETUP AND ALIGNMENT

6.1 Install the thermal-vacuum test fixture, 2374460, in the 4 x 8 chamber at the location shown in Figure 1 and in accordance with Figures 2, 3 and 4. 12-3-74 ✓

6.2 Install window feedthru assembly, 2374453, on the port at rear of chamber. Install the Zygo window on the window feedthru. ✓

6.3 Install the alignment target on the Zygo window. ✓

6.4 Connect roughing pump to the fixture roughing port. ✓

6.5 Install the Far Field Diffraction Instrument (FFDI) on the leveling plate, 2374454, and position it on a wooden-top work bench as shown in Figure 1. ✓

Item #1 6.6 ~~Install the retroreflectors in the Test Article Panel in accordance with Figure 5 and Addendum I.~~

6.7 Mount the first surface mirror on the Test Article Panel so that it is centered over retroreflector position A. ✓

6.8 Install the Test Article Panel in the thermal-vacuum test fixture. ✓

ITEM #9 6.9 Connect thermocouples on the thermocouple fixture to the chamber feedthru, assuring adequate flex loop for free rotation of the fixture. See Figure 6. ✓

6.10 Connect the external thermocouple circuits to the temperature instrumentation. ✓

6.11 Set the rotary vernier micrometer on the T-V test fixture to read 0.252. ✓

6.12 Turn on the FFDI and allow it to warm up. 0830 12/3/74 ✓

6.13 Set the fixture manipulator to the Retro A position at 0° view angle. ✓

6.14 Adjust the FFDI leveling plate position, height and leveling screws so that both the incident and reflected FFDI spots are centered on the alignment target. ✓

Item #1 6.15 ~~Place the spacer block, 2374469-1, on the outside end of the support tube for viewing Retro E.~~

Item #2 6.16 Verify that the FFDI spot is centered on Retro ~~E~~ A. If necessary, move the FFDI vertically and/or laterally to center its spot on Retro ~~E~~ A. ✓

Item #3 6.17 If the FFDI is moved in 6.16, ~~remove the spacer block and~~ repeat 6.14. ✓

6.18 Repeat 6.15 thru 6.17 as needed until the FFDI is properly positioned to be centered on the Retro and aiming perpendicularly to the Retro surface. 12-3-74 ✓

6.19 Remove the mirror from the Test Article Panel. ✓ 12-4-74

Item #4 6.20 Remove the Test Article Panel from the T-V fixture. ~~and reinstall for viewing retroreflectors D, E, and F.~~ ✓

6.21 Remove the alignment target from the Zygo window. Install the FFDI beam shroud and verify that it does not obscure any part of the beam. ✓

Item #5 6.22 Install the retroreflectors in the Test Article Panel in accordance with Figure 5 and [illegible]. 0405 ✓

Item #6 6.23 Install the Test Article Panel in the T-V fixture for viewing retroreflectors D, E, and F. ✓

Item #7 6.24 Verify that the FFDI spot is centered on retro-reflector D. ✓

Item #8 6.25 Verify that the FFDI instrument has been checked and adjusted, as necessary, by the Zygo Representative. ✓

12-4-74

7.0	THERMAL-OPTICAL PROCEDURE	
7.1	Verify that the FFDI has been turned on for warm-up at least four hours before starting tests.	✓
7.2	Isothermal-Ambient Test	
7.2.1	Obtain optical performance data for the reference retroreflector and enter on the Test No. 1 Data Sheet. Number the photographs sequentially and enter the numbers on the Data Sheet.	✓
7.2.2	In accordance with the FFDI Operating Manual, obtain optical data for the D, E, and F retroreflectors at 0 degrees view angle and enter on the Test No. 1 Data Sheet. Number the photographs sequentially (continuing from the last photo in 7.2.1) and enter the numbers on Test No. 1 Data Sheet.	✓
7.2.3	Measure thermocouple temperatures and record on Test No. 1 Data Sheet.	✓
7.2.4	Remove the Test Article Panel from the T-V fixture and reinstall for viewing retroreflectors A, B and C.	✓
7.2.5	Repeat 7.2.2 and 7.2.3.	✓ 12-4-74
7.3	Isothermal-Vacuum Test	
7.3.1	Close the 4 x 8 chamber and start the chamber vacuum pumps per STM 1036.	✓ 0705 12-5-74
7.3.2	Start the fixture roughing pump.	✓
7.3.3	When the chamber is evacuated to a pressure less than 2×10^{-5} torr, enter the actual test conditions on Test No. 2 Data Sheet.	✓
7.3.4	Obtain optical data for the A, B and C retroreflectors at 0 degree view angle and enter the data on the Test No. 2 Data Sheet. Number the photographs sequentially and enter the numbers on Test No. 2 Data Sheet.	✓
Item 12 7.3.4.1	Repeat 7.3.4	✓
7.3.5	Measure thermocouple temperatures and record on Test No. 2 Data Sheet.	✓

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7.3.6 Obtain optical performance data for the reference retroreflector and enter on the Test No. 2 Data Sheet. ✓

7.3.7 Return the chamber environment to ambient conditions per STM 1036. ✓

7.3.8 Remove the Test Article Panel from the T-V fixture and reinstall for viewing retroreflectors D, E, and F. ✓ 12-5-7

7.3.9 Repeat 7.3.1 thru 7.3.5 and 7.3.7. 12-6-74

7.3.1 ✓
7.3.2 ✓
7.3.3 ✓
7.3.4 1145 12-6-74 ✓
7.3.5 ✓
7.3.7 ✓ 12-6-74 1355

Item #13
7.3.9.1 REPEAT 7.3.4

7.4 Isothermal-Ambient Test 1554 12-9-74

7.4.1 Obtain optical performance data for the reference retroflector and enter on the Test No. 3 Data Sheet. Number the photographs sequentially and enter the numbers on the Data Sheet. ✓

7.4.2 In accordance with the FFDI Operating Manual, obtain optical data for the D, E and F retroflectors at 0 degree view angle and enter the data on the Test No. 3 Data Sheet. Number the photographs sequentially and enter the numbers on Test No. 3 Data Sheet. 1630 12-9-74 ✓

Item #13 ~~7.4.2.1~~ ~~Repeat 7.4.2~~

7.4.3 ~~Measure thermocouple temperatures and record on Test No. 3 Data Sheet.~~
DELETE ITEM #15

7.4.4 Remove the Test Article Panel from the T-V fixture and reinstall for viewing retroreflector A, B and C. 12-10-74 1015 ✓

7.4.5 Repeat 7.4.2 and 7.4.3. ✓
7.4.5.1 REPEAT 7.4.1 1125 12-10-74 ✓

7.5 Remove the Test Article Panel from the fixture and return it to LAGEOS Engineering

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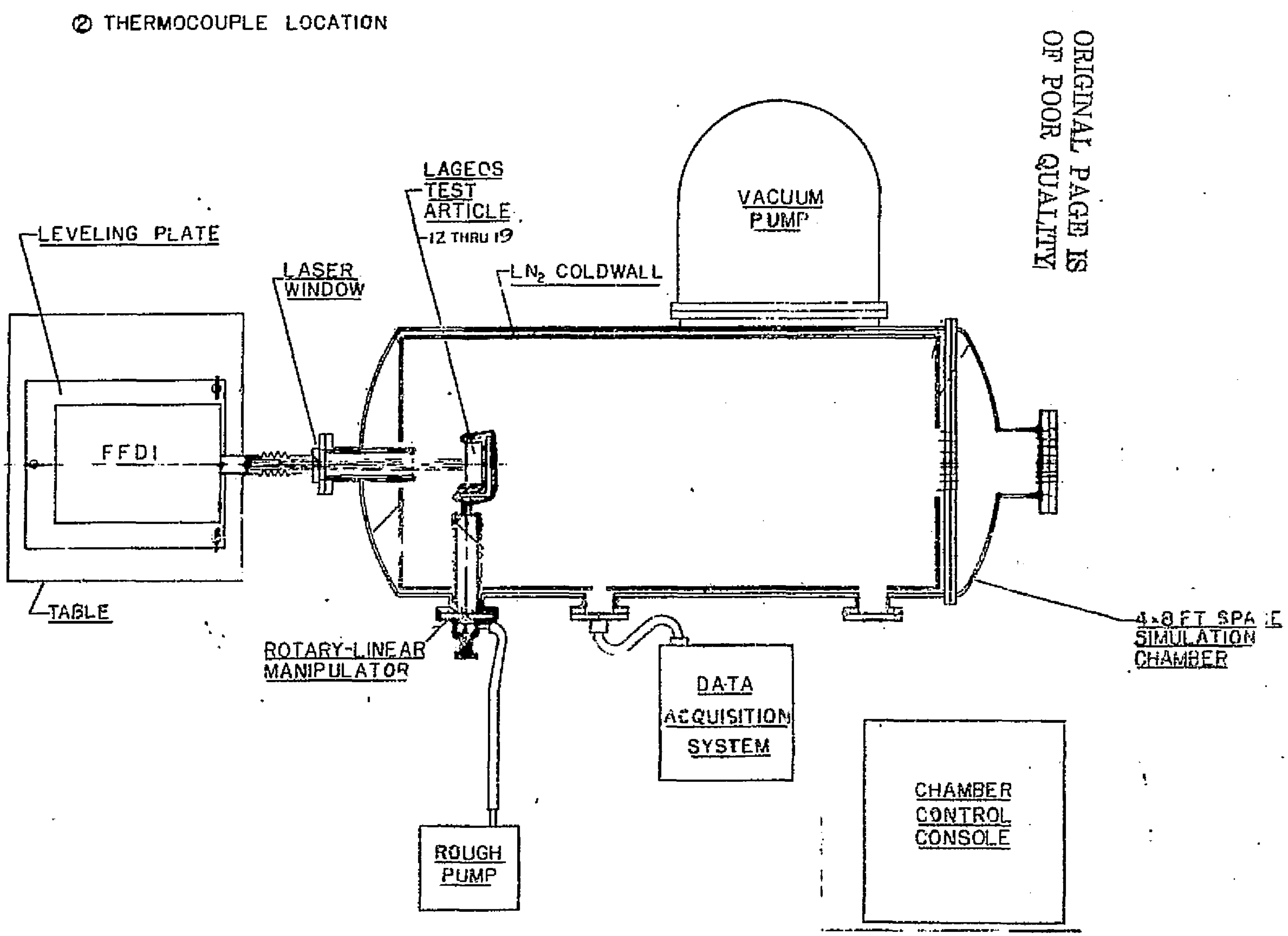

LAGEOS TEST SETUP - THERMAL-VACUUM

FIGURE 1

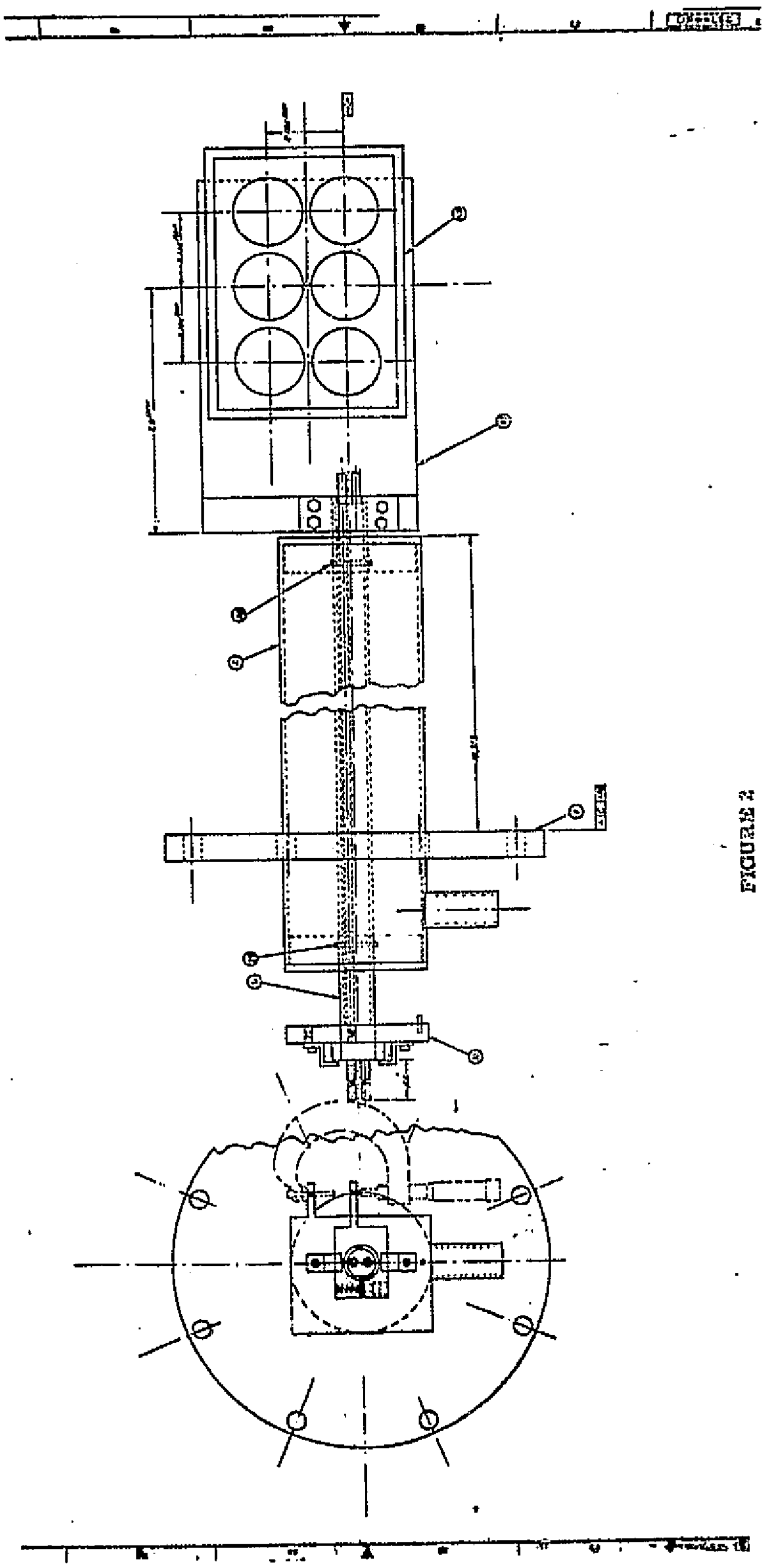

FIGURE 2

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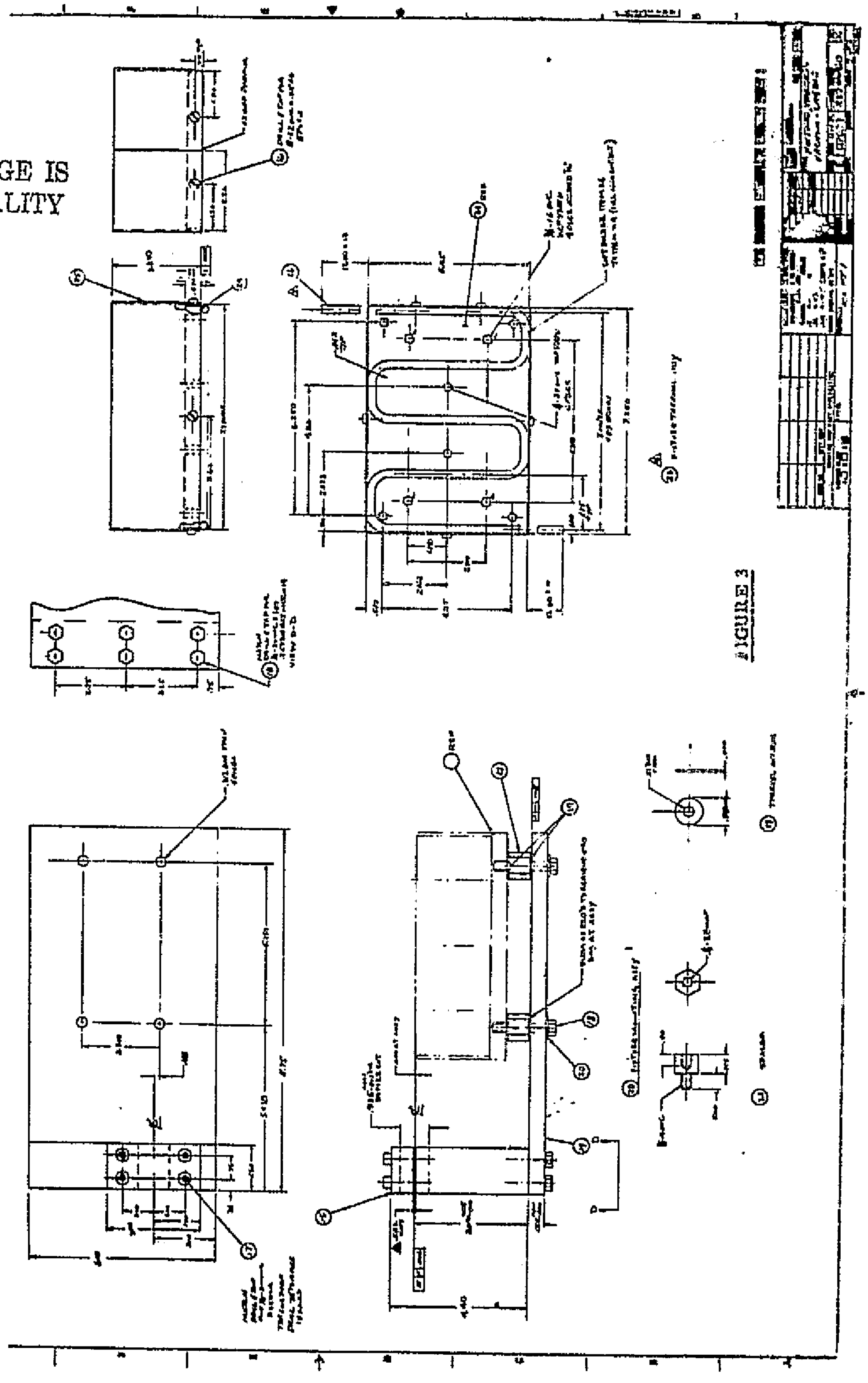

FIGURE 3

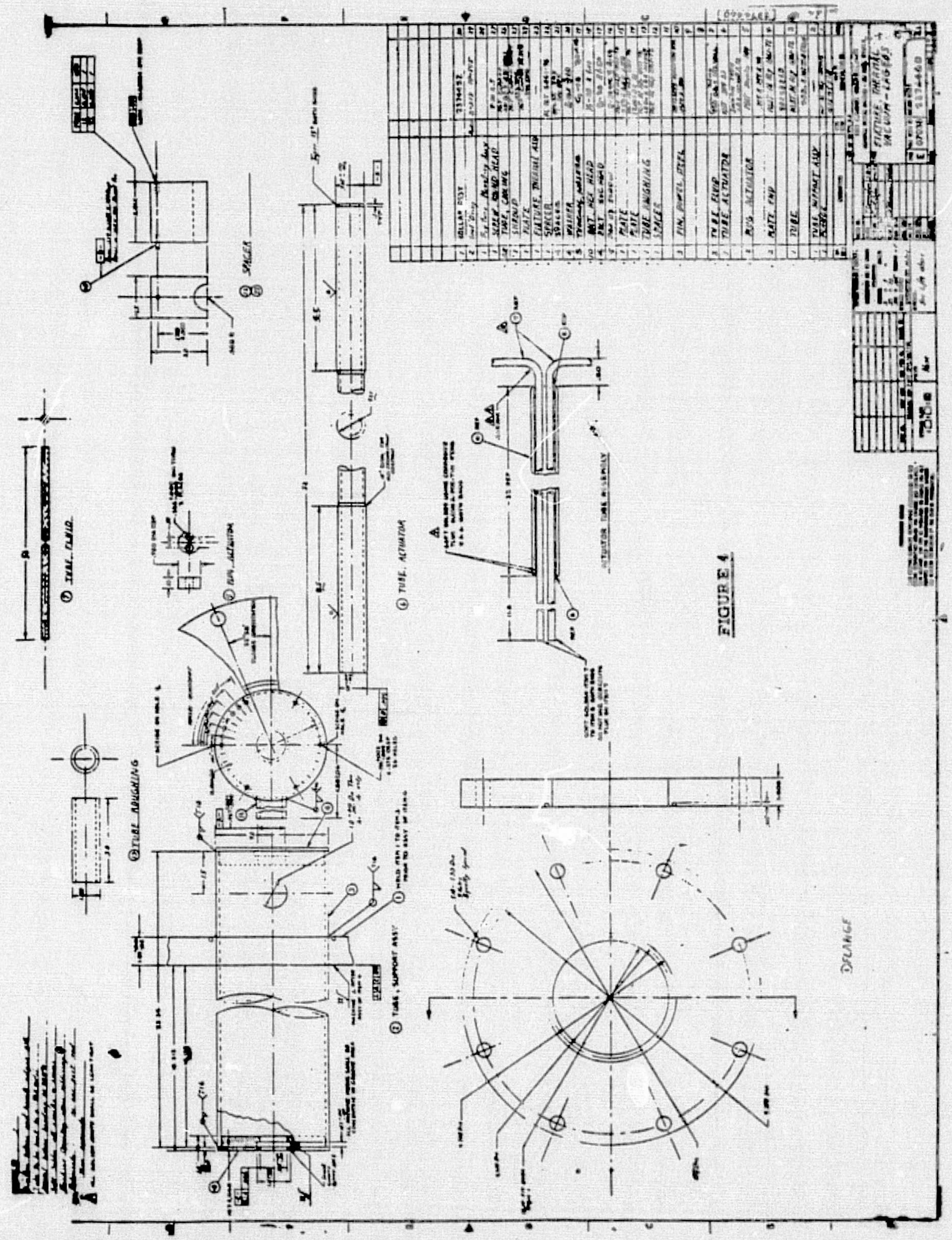

FIGURE 4

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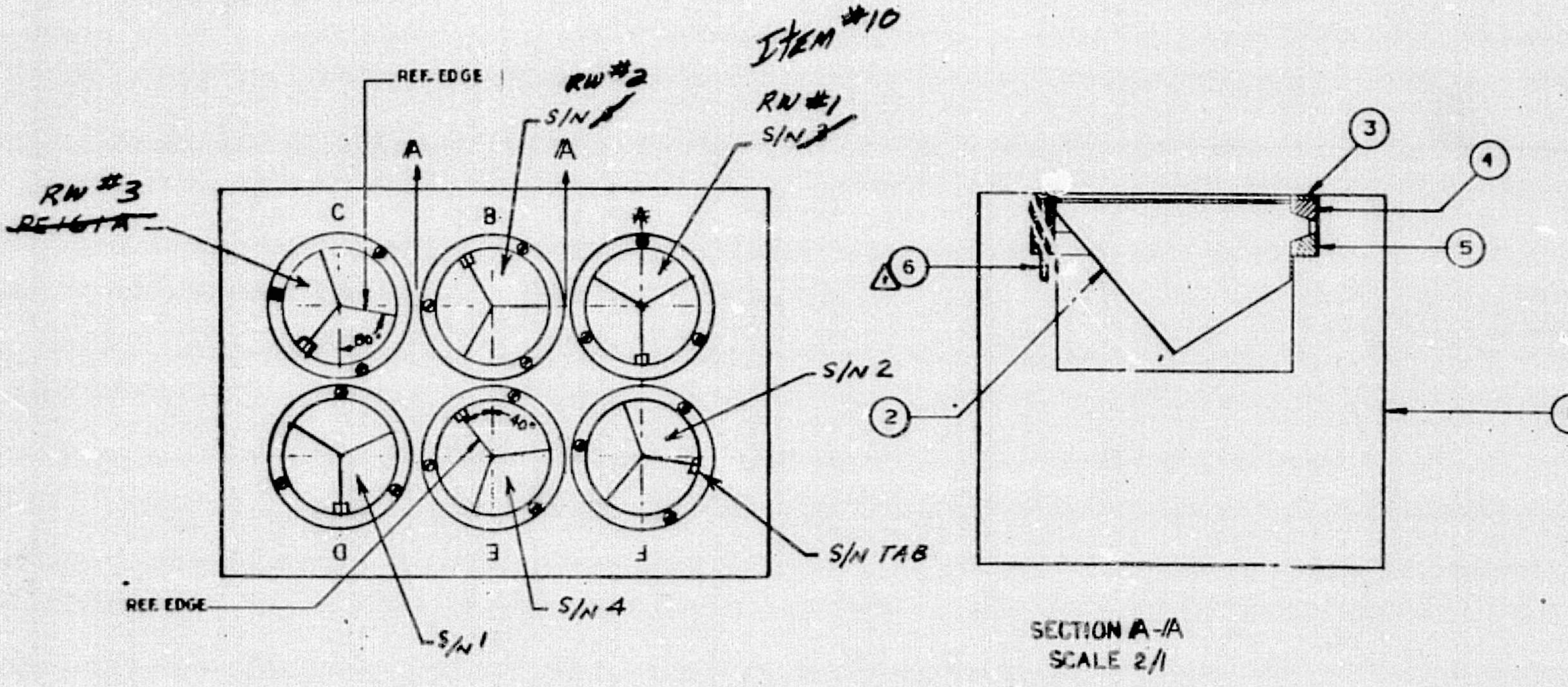
NOTES:

1. TORQUE ITEM 6 TO 1.4 $^{+0}_{-.2}$ IN-LBS.
2. CLEAN, HANDLE AND ASSEMBLE IN ACCORDANCE WITH 2374465



	RETROREFLECTORS	
	S/N	DESCRIPTION
	1	9118-1001 (ORIGINAL)
	2	9118-1001 (ORIGINAL)
RW#1	~~3~~	9118-1001 (REWORKED)
	4	9118-1001 (ORIGINAL)
RW#2	~~5~~	9118-1001 (REWORKED)
RW#3	~~RE1G1A~~	100-2664-001 (REWORKED)

QTY REQD	DESCRIPTION	CODE IDENT	PART OR SPECIFICATION NO.	ITEM
12	SCREW		MS 35202-8	6
6	LOWER RING		2374462	5
6	UPPER RING		2374461	4
6	RETAINER RING		2374463	3
6	RETRO		AS NOTED	2
1	PANEL		2374464	1

LIST OF MATERIALS

LAGEOS TEST ARTICLE ASSEMBLY

FIGURE 5

LAGEOS Retroreflector Performance Improvement - Thermal-Optical Test

NO. TP 2374470

REV. NO. X1

DATE 18 November 197

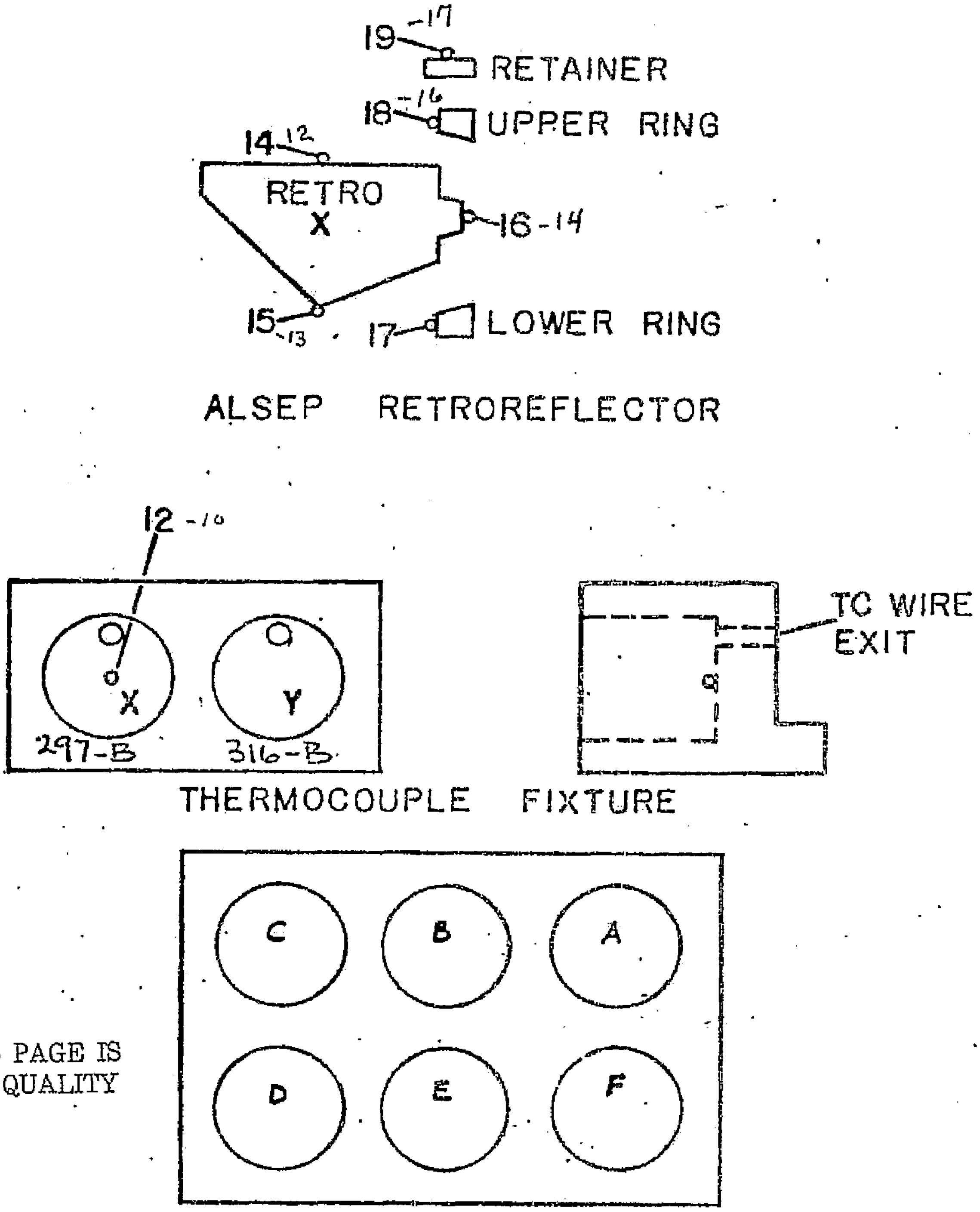


FIGURE 6 THERMOCOUPLE LOCATIONS

8.0 DATA SHEETS

8.1 Test Sequence: As-Run Summary

Test No.	Description	Photo Nos.	Date	Time
#1	Isothermal-Amb.	1-7	12-4-74	1625-1705
#2	Isothermal-Vac	8-14	12-5-74	1017-1044
#2	Isothermal-Vac	15-21	12-6-74	1044-1122
#3	Isothermal-Amb	22-~~24~~25	12-9-74	1554-1630
#3	Isothermal-Amb	26-29	12-10-74	1015-1125

Bendix Aerospace Systems Division

8.2 Test Conditions and Data Log

Isothermal - Ambient

LAGEOS Retroreflector Performance Improvement - Thermal-Optical Test

NO.	REV. NO.
TP 2374470	X1
PAGE 15 OF 19	
DATE 18 November 197	

Test No. *1*

TEST CONDITIONS

Temperature: Ambient
Pressure: *Ambient*
Field View Angle: 0 Degrees

Test Date: *12-4-74*
Time: *1625*

NOTE: *DAS Time @ Temps Retro D is 16:38:11.*
DAS Time @ Temps Retro A is 17:02:31

TEST DATA *Per P 7.2.2 & 7.2.5*

Data	Ref. Retro	Retro A	Retro B	Retro C	Retro D	Retro E	Retro F
Photo No.	*1*	*5*	*6*	*7*	*2*	*3*	*4*
Laser	*.82*	*.81*	*.81*	*.81*	*.82*	*.82*	*.82*
FFDP-Annular	*.16*	*.15*	*.15*	*.13*	*.10*	*.12*	~~*.09*~~ *.10*
Ratio-Annular	*.19*	*.18*	*.18*	*.16*	*.11*	*.13*	~~*.10*~~ *.12*
Ratio-Full Field	*1.18*	*1.19*	*1.16*	*1.20*	*1.19*	*1.22*	*1.20*
Bias	~~*.005*~~ *.010*	*.010*	*.010*	*.010*	*.010*	*.010*	*.010*
FFDP-Full Field ~~TC No. 13 °C~~	*1.00* ---	*1.00*	*.99* ---	*1.01* ---	*1.00*	*1.03* ---	*1.01* ---
TC No. 14 °C *DAS 002*	---	~~[illegible]~~ *25.6*	---	---	~~[illegible]~~ *24.5*	---	---
TC No. 15 °C *DAS 003*	---	~~[illegible]~~ *25.6*	---	---	~~[illegible]~~ *25.0*	---	---
TC No. 16 °C *DAS 004*	---	~~[illegible]~~ *25.6*	---	---	~~[illegible]~~ *24.5*	---	---
TC No. ~~17~~ *12* °C *DAS 001*	---	~~[illegible]~~ *25.0*	---	---	~~[illegible]~~ *24.0*	---	---
TC No. 18 °C *DAS 005*	---	~~[illegible]~~ *25.0*	---	---	~~[illegible]~~ *24.5*	---	---
TC No. 19 °C *DAS 006*	---	~~[illegible]~~ *25.0*	---	---	~~[illegible]~~ *24.5*	---	---

Item #11

TEST CONDITIONS

Temperature: Ambient
Pressure: <2x10^{-5} ACTUAL 9.1x10^{-6}
Field View Angle: 0 Degrees

Test Date: 12-5-74
Time: 0952

NOTE: DAS TIME @ TEMPS · RETRO A (PHOTO 9)
15 1017:37
DAS TIME @ TEMPS. RETRO A (PHOTO 12)
15 1044:30

TEST DATA

ITEM #12 Isothermal-Vacuum

		P 7.3.4			P 7.3.4.1		
Data	Ref. Retro	Retro A	Retro B	Retro C	Retro A ~~D~~	Retro B ~~E~~	Retro C ~~F~~
Photo No.	8	9	10	11	12	13	14
Laser	.82	.82	.82	.82	.82	.82	.82
FFDP-Annular	.15	.15	.15	.13	.14	.15	.13
Ratio-Annular	.18	.17	.18	.16	.17	.18	.15
Ratio-Full Field	1.17	1.17	1.12	1.11	1.14	1.13	1.12
Bias (FFDP)	.005	.005	.005	.005	.005	.005	.004
ITEM #11 FFDP-Full Field ~~TC No. 12 °C~~	.99	.99	.94	.94	.96	.96	.95
TC No. 14 °~~C~~F	---	(-2.79MV) 70	---	---	(-2.78MV) 70	---	---
ITEM #14 TC No. 15 °~~C~~F	---	(-2.78MV) 70	---	---	(-2.78MV) 70	---	---
TC No. 16 °~~C~~F	---	(-2.79MV) 70	---	---	(-2.78MV) 70	---	---
TC No. [illegible] °~~C~~F	---	(-2.82MV) 69	---	---	(-2.82MV) 69	---	---
TC No. 18 °~~C~~F	---	(-2.77MV) 70	---	---	(-2.77MV) 70	---	---
TC No. 19 °~~C~~F	---	(-2.78MV) 70	---	---	(-2.77MV) 70	---	---

Bendix Aerospace Systems Division

LAGEOS Retroreflector Performance Improvement - Thermal-Optical Test

Test Conditions and Data Log

Test No. ~~1~~ 2

NO.	REV. NO.
TP 2374470	

PAGE ~~15~~ 169 OF 19

DATE 18 November 197

ORIGINAL PAGE IS OF POOR QUALITY

TEST CONDITIONS

Temperature: Ambient

Pressure: < 2x10^-5 ACTUAL 3.6x10^-6 TORR

Field View Angle: 0 Degrees

Test Date: 12-6-74

Time: 1044

NOTE: DAS TIME & TEMPS. RETRO D (PHOTO 15)
15 1044:53
DAS TIME & TEMPS. RETRO D (PHOTO 19)
15 1122:29

Item #13

TEST DATA

Data	Ref. Retro	P 7.4.2 Retro ~~A~~ D	Retro ~~B~~ E	Retro ~~C~~ F	P 7.4.2.1 Retro D	Retro E	Retro F
Photo No.	15	16	17	18	19	20	21
Laser	.78	.78	.78	.78	.78	.78	.78
FFDP-Annular	.15	.093 * ~~.08~~	.102 * ~~.09~~	.085 * ~~.08~~	.095 * ~~.08~~	.104 * ~~.09~~	.088 * ~~.08~~
Ratio-Annular	.19	.10	.11	.106 * ~~.09~~	.10	.11	.10
Ratio-Full Field	1.20	1.15	1.19	1.17	1.15	1.18	1.16
Bias (FFDP)	.006	.006	.006	.006	.007	.007	.007
Item #11 FFDP-FULL FIELD ~~TC No. 12 °C~~	.96	.92	.95	.94	.92	.95	.94
TC No. 14 °~~C~~F	---	-2.63 mv 75	---	---	-2.64 mv 74	---	---
TC No. 15 °~~C~~F	---	-2.62 mv 75	---	---	-2.63 mv 75	---	---
TC No. 16 °~~C~~F	---	-2.63 mv 75	---	---	-2.63 mv 75	---	---
TC No. 12 °~~C~~F	---	-2.66 mv 74	---	---	-2.67 mv 73	---	---
TC No. 18 °~~C~~F	---	-2.62 mv 75	---	---	-2.63 mv 75	---	---
TC No. 19 °~~C~~F	---	-2.62 mv 75	---	---	-2.63 mv 75	---	---

* USING X 10 SWITCH

Bendix Aerospace Systems Division

LAGEOS Retroreflector Performance Improvement - Thermal-Optical Test

NO. TP 2374470 | REV. NO. X1

PAGE 17 OF 19

DATE 18 November 197

TEST CONDITIONS

Temperature: Ambient ~70°F; 69°F (12-9-74; 12-10-74)

Pressure: Ambient

Field View Angle: 0 Degrees

Test Date: 12-9-74 (START) 12-10-74 (COMP)

Time: 1554 (START) 1125 (COMP)

NOTE:

Isothermal - Ambient

Test No. 3

TEST DATA

Data	Ref. Retro (ITEM #16)		Retro A (PARA 7.4.5)	Retro B (PARA 7.4.5)	Retro C (PARA 7.4.5)	Retro D (PARA. 7.4.2)	Retro E (PARA. 7.4.2)	Retro F (PARA. 7.4.2)
Photo No.	29	25	28	27	26	24	23	22
Laser	.74	.74	.75	.76	.75	.74	.74	.75
FFDP-Annular	.15	.14	.13	.14	.12	.094* ~~.09~~	.10	.088 ~~.08~~
Ratio-Annular	.19	.19	.17	.18	.15	.11	.13	.11
Ratio-Full Field	1.21	1.22	1.17	1.15	1.18	1.15	1.18	1.16
Bias (FFDP)	.005	.007	.005	.005	.005	.007	.007	.007
FFDP-Full Field ~~TC No. 12 °F~~ (Item #11)	.93	.94	.91	.90	.92	.88	.91	.89
TC No. 14 °F	---		X	---	---	X	---	---
TC No. 15 °F	---		X	---	---	X	---	---
TC No. 16 °F	---		X	---	---	X	---	---
TC No. 17 °F	---		X	---	---	X	---	---
TC No. 18 °F	---		X	---	---	X	---	---
TC No. 19 °F	---		X	---	---	X	---	---

DELETE ITEM #15

9.0 PROCEDURE VARIATIONS

#	Ref. Para.	Variation Description	BxA T.C.	Therm. Eng.	Prog. Mgr.
1	6.6 6.15	DELETE ENTIRE PARAGRAPH	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
2	6.16	CHANGE "--RETRO B--" to "--RETRO A--" 2 PLACES	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
3	6.17	DELETE "--REMOVE the SPACER block AND--"	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
4	6.20	DELETE "--AND REINSTALL FOR VIEWING RETROREFLECTORS D, E, AND F."	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
5	6.22	ADD PARAGRAPH: "INSTALL THE RETROREFLECTORS IN THE TEST ARTICLE PANEL IN ACCORDANCE WITH FIGURE 5 AND ADDENDUM 1."	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
6	6.23	ADD PARAGRAPH: "INSTALL THE TEST ARTICLE PANEL IN THE T-V FIXTURE FOR VIEWING RETROREFLECTORS D, E, AND F."	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
7	6.24	ADD PARAGRAPH: "VERIFY THAT THE FFDI SPOT IS CENTERED ON RETROREFLECTOR D."	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
8	6.25	ADD PARAGRAPH: "VERIFY THAT THE FFDI INSTRUMENT HAS BEEN CHECKED, AND ADJUSTED, AS NECESSARY, BY THE ZYGO REPRESENTATIVE.	12-3-74	E.A.G. 12-3-74	JmB 12-3-74
9	6.9	T.C. #17 LEAD WIRE INACCESSIBLE IN INSULATION BLANKET, DELETE REQUIREMENT FOR TC #17 RETRO LOWER MOUNTING RING, THERMAL DATA.	12-4-74	E.A.G. 12-4-74	JmB 12-4-74

9.0 PROCEDURE VARIATIONS

#	Ref. Para.	Variation Description	BxA T.C.	Therm. Eng.	Prog. Mgr.
10	FIG. 5	RETRO S/N'S CHANGED BY ZYGO IN REWORK EFFORT. CHANGE S/N'S	[signature] 12-4-74	E.A.G. 12-4-74	JMB 12-4-74
11	8.2	Change Data Log to delete TC #? data and add FFDP-Full Field data.	[signature] 12-4-74	E.A.G. 12-4-74	JMB 12-4-74
12	7.3.4.1	Add paragraph "Repeat 7.3.4."	[signature] 12-5-74	E.A.G. 12-5-74	JMB 12-5-74
13	~~7.4.2.1~~ 7.3.9.1	Add paragraph "Repeat 7.3.4 ~~7.4.2~~."	[signature] 12-5-74	E.A.G. 12-5-74	JMB 12-5-74
14	PAGE 16 16A 17	CHANGE °C TO °F	[signature] 12-5-74	E.A.G. 12-5-74	JMB 12-5-74
15	PAGE 17 7.4.3	DELETE TC READINGS DELETE "MEASURE THERMOCOUPLE TEMPERATURES ..... SHEET"	[signature] 12-5-74	E.A.G. 12-9-74	JMB 12-9-74
16	PAGE 17	ADD COLUMN FOR FINAL REF. RETRO DATA		E.A.G. 12-10-74	JMB 12-10-74

QUALITY ASSURANCE DEPT.
TEST DISCREPANCY REPORT

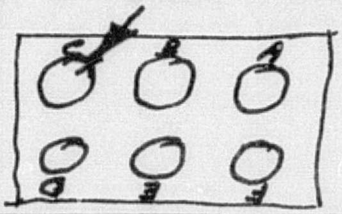
1 1 TDR C4015

8 TEST PROCEDURE NO.	REV.	19 PART NAME	32 SERIAL NO.	38 MO. DAY YR.
2374470	X1	TEST ART PANL		1 2 0 4 7 4

44 NAME OF TEST	58 PROGRAM NO.	63 LOC.	PARA NO.	PART NO.	REV
THERM-OPTICAL	~~[illegible]~~ 63651	TV	6.22		

DESCRIPTION OF ANOMALY

While installing the retroreflectors, an aluminum retaining screw (2-56) seized in the aluminum Test Article Panel. Screw head was twisted off while attempting to remove the screw. Screw location is at "C" retro location, at the 1 o'clock position.



ORIGINATOR: J P Monroe

SUMMARY OF TROUBLESHOOTING/RESOLUTION

No troubleshooting performed.
Use as is, with (2) screws retaining the retro.

1	TEST OPERATOR	5	CONTRACT-PURCHASED FUNCTIONAL TEST EQUIP.
2	BXA FACILITY DEFECT	6	TEST FIXTURING DESIGN ERROR
3	TEST SET-UP	7	FACILITY OPERATION PROCEDURE ERROR
4	TEST PROCEDURE	8	HARDWARE DISCREPANCY (CONVERTED TO DR)
65 CODE 00 (ENTER ONE OF THE ABOVE)		0	OTHER (EXPLAIN)=

CAUSE OF ANOMALY:

Screw & block were both thoroughly degreased & cleaned. Non-lubricated interface, aluminum screw to aluminum tapped hole resulted in seizing. Degreasing and cleaning processing are required by T. Proc.

CLASSIFICATION OF DEFECT

CR	CRITICAL
MA	MAJOR
MI	MINOR
PA	PAPERWORK

67 CODE

DR	DISCREPANCY REPORT	RR	RWK OR REPAIR EQUIP.
WR	WORK REQUEST	CT	CONTINUE TEST
CRD	CHANGE REQUEST DIRECTIVE	OT	OTHER EXPLAIN
TDR	TEST DISCREPANCY REPORT		(ENTER IN BLOCK 69)

69 CODE TDR

LOCATION CODES (ENTER IN BLOCK 63 ABOVE)

CT = COMPONENT TEST LAB	TV = THERMAL-VACUUM LAB
SA = SUBASSEMBLY TEST LAB	VL = VIBRATION LAB
ET = EXPERIMENT TEST LAB	CL = CALIBRATION LAB
ST = SYSTEM TEST LAB	EM = EMI/SCREEN ROOM
TL = TRANSMITTER LAB	CC = CLIMATIC CHAMBER
PL = P.S.E. LAB	HB = HIGH BAY AREA
	OP = OUT OF PLANT

Evaluation of possible lubricants and/or change of screw material should be made prior to assembly of the LAGEOS Flight Article.

TEST CONDUCTOR	BXA QA REPRESENTATIVE	GOV'T SOURCE REPRESENTATI
John Brueger	J P Monroe 12-4-74	N/A

210-788

10.0 TEST SIGN-OFF SHEET

C.F. Shggy 12-10-74
Environmental/Quality Test T-V Engineer

12-10-74
Environmental/Quality Test Conductor

Erik A. Granholm 12-10-74
LAGEOS Thermal Engineer

12-10-74
LAGEOS Program Manager

1.0 This addendum specifies the LAGEOS Test Article assembly. Hardware items included are: Test Article Panel, PN 2374464; Thermocouple Fixture, PN 2374466; LAGEOS Retroreflectors; and ALSEP Retroreflectors.

2.0 ASSEMBLY OPERATIONS

2.1 Clean the Test Article Panel per Dwg. 2374465. 11-25-74 ✓

2.2 Clean the LAGEOS Retroreflectors per Dwg. 2374465. 11-25-74 ✓

2.3 Install the LAGEOS Retroreflectors in the Test Article Panel as shown in Figure 5. 12-4-74 ✓

CAUTION: OBSERVE ALL CLEANLINESS AND SPECIAL HANDLING REQUIREMENTS PER DWG. 2374465 TO AVOID CONTAMINATION OF THE RETROREFLECTOR SURFACES.

2.4 On completion of assembly operations, place the assembly in a plastic bag for temporary storage protection. 12-4-74 ✓

2.5 Verify that the ALSEP Retroreflectors, thermocouples, and the Thermocouple Fixture are still assembled per TP 2374455, Addendum I. 11-27-74 ✓

RELIABILITY		REVISIONS			
APPD	PREDICTION	LTR	DESCRIPTION	DATE	CONFIG MGT APPV'D
		X1	EXPERIMENTAL RELEASE ER 1922-18	7/30/74	
		X2	REVISED SH'S 2 & 3 PER 2374465-X2	11/26/74	L.D.

TABLE OF CONTENTS

DRAWING AND PART APPLICATION

PART NO	NEXT ASSY	END ITEM NO.	SERIAL NO.
2374458	N/A	N/A	N/A
2374466	N/A	N/A	N/A

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES.

MATERIAL: —

DRAWING CLASS A ☐ B ☐ C ☒

CONTR NO.	NAS 8-30658	
DRAWN	J. Bueraga	7-30-74
CHECKED	E. Grainon	7-30-74
STRESS/WT		
DSGN SUPV		
PROJ ENGR	C. Bunge	7-30-74
QUAL CONT		
SYS SPT		
DSGN APPL		
MFG		
CUSTOMER		

THE BENDIX CORPORATION
AEROSPACE SYSTEMS DIVISION – ANN ARBOR, MICHIGAN

TITLE
LAGEOS Cleaning, Handling and Assembly Requirements

SIZE	CODE IDENT NO.	DRAWING NUMBER	REV
A	07038	2374465	X2

SCALE – | WEIGHT | SHEET 1 OF 5

xA 341B-1

1.0 PURPOSE

The purpose of this procedure is to define the requirements for cleaning, assembly and handling the LAGEOS Test Article (2374458) and its parts, the Thermocouple Fixture (2374466) and its parts, and the Fixture Thermal Assembly (2374460-23).

2.0 SCOPE

This document specifies the special procedures for cleaning LAGEOS test hardware prior to assembly and test. It also specifies special precautions to be observed in the handling and assembly of the test hardware. Detail assembly operations are specified in Addendum I to the Thermal/Optical Test Procedures (TP 2374455 and TP 2374470).

3.0 REQUIREMENTS

3.1 Cleaning Procedures

3.1.1 Aluminum Parts Cleaning - Prior to assembly, the Test Article Panel (2374464), the Thermocouple Fixture Panel (2374466-1) and the retainer rings (2374463) shall be cleaned as follows: 11/25/74 JMB 11/25/74 JMB

A. Ultrasonic clean in Freon TF for a minimum of 10 minutes.

B. Vapor degrease in Freon TF for a minimum of 5 minutes.

C. Ridoline No. 322 Solution - Immerse to remove all surface organic contamination for a minimum of 5 minutes. Wipe all surfaces and brush all fillets, holes and tapped holes to aid cleaning.

D. Rinse, for 30 seconds minimum, in agitated room temperature tap water.

E. Deoxidizer No. 17 Solution - Immerse, to remove all smut and surface oxidation, for a minimum of 5 minutes.

F. Rinse, for 30 seconds minimum, in agitated room temperature tap water.

G. Final rinse, for 30 seconds minimum, in agitated deionized water. Bake at 250°F for 2 hours to air dry.

H. Bag, tag and seal in teflon bag, handling with clean, lint-free white gloves.

3.1.2 Non-Aluminum Parts Cleaning (Excluding Retroreflectors) - Prior to assembly, the upper and lower mounting rings (2374461 and 2374462), the mounting screws, the tie-down bolts and the Fixture Thermal Assembly (2374460-3) shall be cleaned as follows:

11/25/74
JMB

A. Ultrasonic clean in Freon TF for a minimum of 10 minutes.

B. Vapor degrease in Freon TF for a minimum of 5 minutes.

C. Ridoline No. 322 Solution - Remove organic contamination by immersion for a minimum of 5 minutes. Wipe all surfaces and brush all fillets, holes and threads to aid cleaning.

D. Rinse, for 30 seconds minimum, in agitated room temperature tap water.

E. Rinse, for 30 seconds minimum, in agitated deionized water. Bake at 250°F for 2 hours to air dry.

F. Bag, tag and seal in teflon bag, handling with clean, lint-free white gloves.

3.1.3 Retroreflector Cleaning - If only lint or dust is evident on the retroreflector, it shall be cleaned by blowing it away, using a clean sterilized squeeze-bulb syringe, or by brushing it away, using a fine, camels-hair lens brush. If ~~smudges~~, oil, films, finger marks, etc., are evident, cleaning shall be as follows:

Remove contamination by rinsing in laboratory quality ethyl alcohol. Bake at 160°F to air dry. If grease or dirt is not removed by rinsing, wipe with degreased, sterile cotton swabs moistened with ethyl alcohol or with lens tissue pad moistened with ethyl alcohol. Allow to air dry as unit is being wiped. Methyl alcohol may be used if no ethyl alcohol is available. Wrap the retroreflectors, individually, in several layers of lens tissue and store in foam-lined individual containers.

If the retroreflectors are aluminum-coated, this coating shall be removed prior to optical tests. Immerse the retroreflectors, individually, in muriatic acid until coating is removed. Rinse for 30 seconds minimum in agitated room temperature tap water. Rinse for 30 seconds minimum in agitated room temperature deionized water. Inspect for grease or dirt to establish whether further cleaning is necessary. A second choice material for coating removal is potassium hydroxide.

S/H 1,2,4
11/25/74
JMB.

THE BENDIX CORPORATION AEROSPACE SYSTEMS DIVISION ANN ARBOR, MICHIGAN	SIZE A	CODE IDENT NO. 07038	DRAWING NUMBER 2374465	REV X2
	SCALE	WEIGHT	SHEET 3 OF 5	

3.2 Handling Precautions

A. All parts shall remain in sealed bags until ready for assembly.

B. Parts, after removal from bags, shall be handled only with clean lint-free white gloves.

C. Tools and handling aids used to handle or torque parts shall be cleaned prior to use, to remove grease and contaminants from the surfaces which contact the test parts.

D. Retroreflector handling shall be minimized and shall be done only with gloved hands or with a special tool which provides a soft inert plastic-coated three-point contact with the retroreflector. Care shall be taken to avoid contact with the back faces or edges and to prohibit any surface contamination.

3.3 Assembly Precautions

Final assembly (after cleaning) of the Test Article panel and the Thermocouple Fixture onto the Fixture Thermal Assembly and installation of retroreflectors into the Test Article Panel and the Thermocouple Fixture shall be accomplished in accordance with the applicable drawings, the Thermal/Optical Test Procedure (TP 2374455-Addendum I) and the following precautions:

A. Assembly shall be done on a laminar-flow bench. Parts shall be removed from their storage bags on the bench and shall be rebagged if it is necessary to remove them from the bench, prior to completing assembly.

B. The Test Article and Thermocouple Fixture shall each be covered with a protective cover, consisting of a transparent plastic sheet (e.g. "Saran-wrap" or "Handi-wrap"), over their front surfaces, to minimize contamination after installation on the Fixture Thermal Assembly and prior to removal from the bench. The plastic sheet shall only be removed during isothermal/ambient thermal/optical tests, during vibration exposure and just prior to the final preparations for closing the thermal/vacuum chamber. Except during isothermal/ambient tests, if the thermal/vacuum chamber is to be left open for longer than 15 minutes, the plastic sheet shall be re-installed during the open period.

The entire assembly of the Test Article, Thermocouple Fixture and Fixture Thermal Assembly shall be enclosed in a sealed plastic bag for temporary storage, if the assembly is not to be immediately installed in the chamber.

APPENDIX D

LAGEOS ADD-ON OPTICAL TESTS --

FAR-FIELD DIFFRACTION PATTERN PHOTOGRAPHS

Note:

a) This data is identified by Test Number and Photograph Number; test conditions for each photograph are identified in Appendix C.

b) The FFDI scale factor is 1.47 arc sec/mm The centimeter scale provided on each page must be used for any length measurements because of scale variations during document reproduction.

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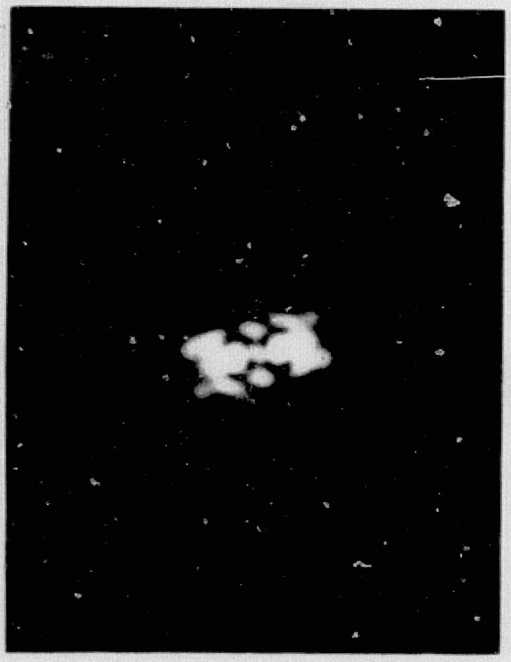
OF POOR QUALITY

LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI



Test No. 1A
Retro: CALIB.
Photo No. 1
Exposure Time: 1/500 SEC

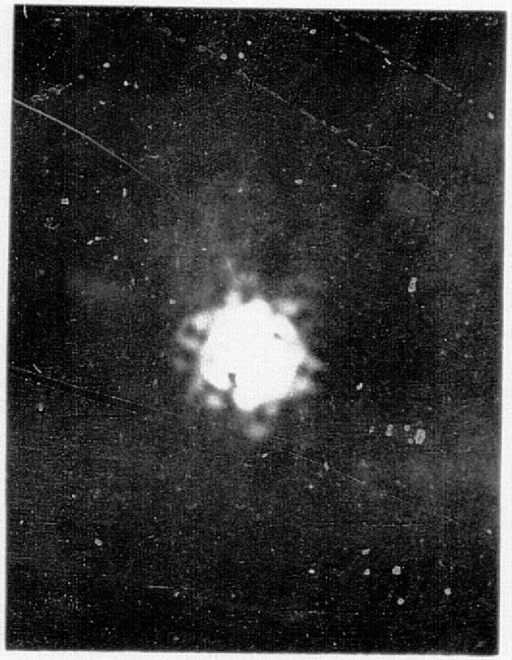
Test No. 1A
Retro: D
Photo No. 2
Exposure Time: 1/250 SEC

Test No. 1A
Retro: E
Photo No. 3
Exposure Time: 1/250 SEC

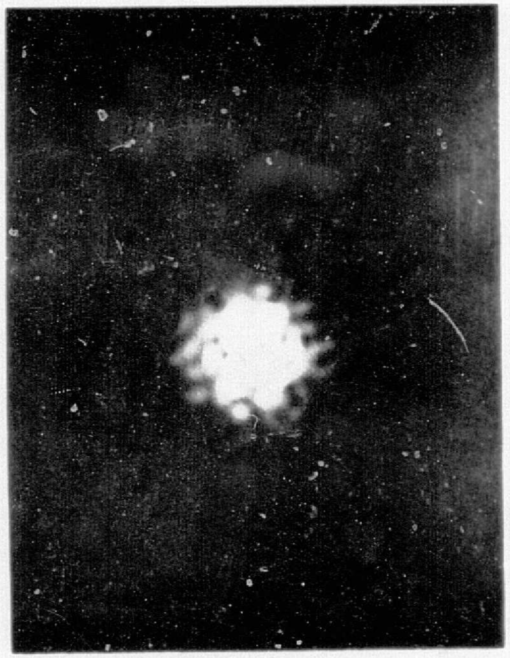
LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI

cm 1 2 3

Test No. 1A
Retro: F
Photo No. 4
Exposure Time: 1/250 sec



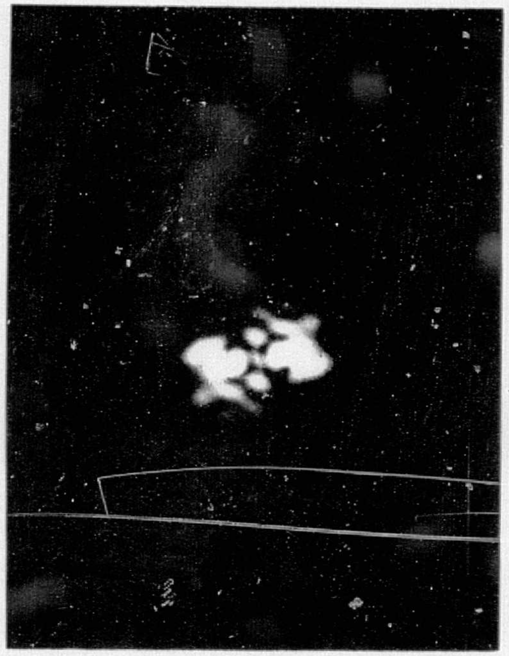
Test No. 1A
Retro: A
Photo No. 5
Exposure Time: 1/250 sec



Test No. 1A
Retro: F
Photo No. 6
Exposure Time: 1/250 sec

LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI

cm 1 2 3



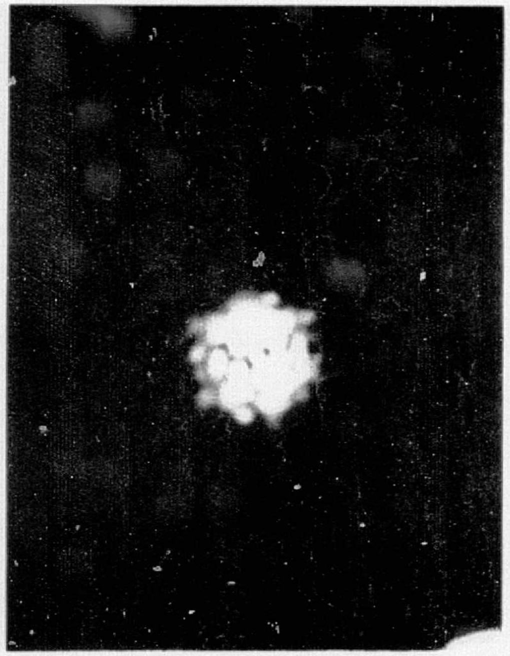
A-9

Test No. 1A
Retro: C
Photo No. 7
Exposure Time: 1/250 SEC

Test No. 2A
Retro: CALIB
Photo No. 8
Exposure Time: 1/500 SEC

Test No. 2A
Retro: A
Photo No. 9
Exposure Time: 1/250 SEC

LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI

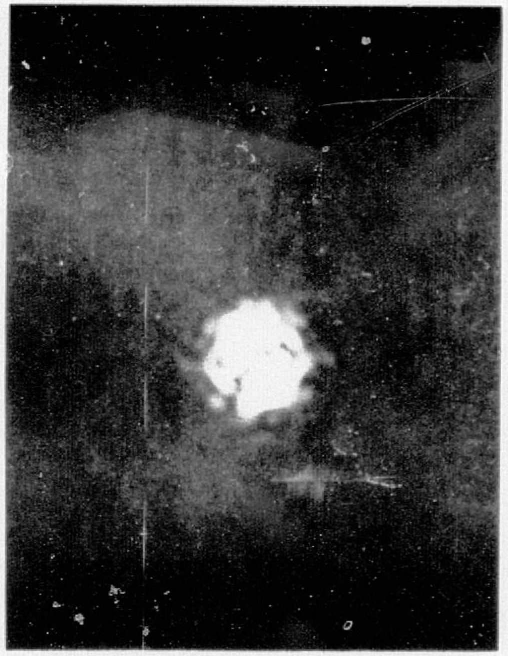


A-10

Test No. 2 A
Retro: B
Photo No. 10
Exposure Time: 1/250 SEC

A-11

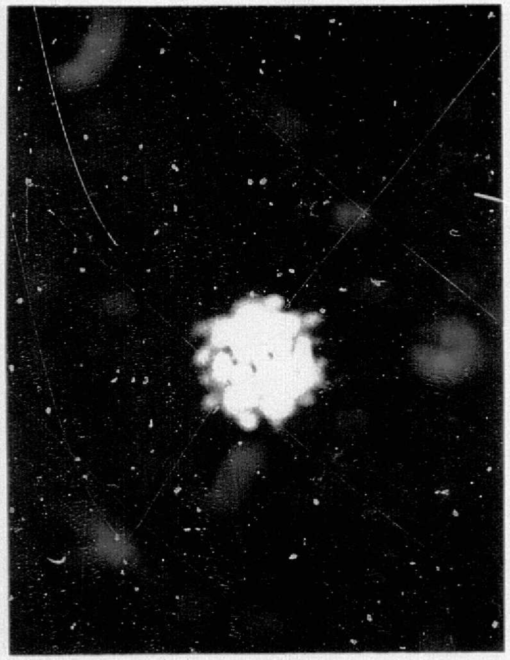
Test No. 2A
Retro: C
Photo No. 11
Exposure Time: 1/250 SEC



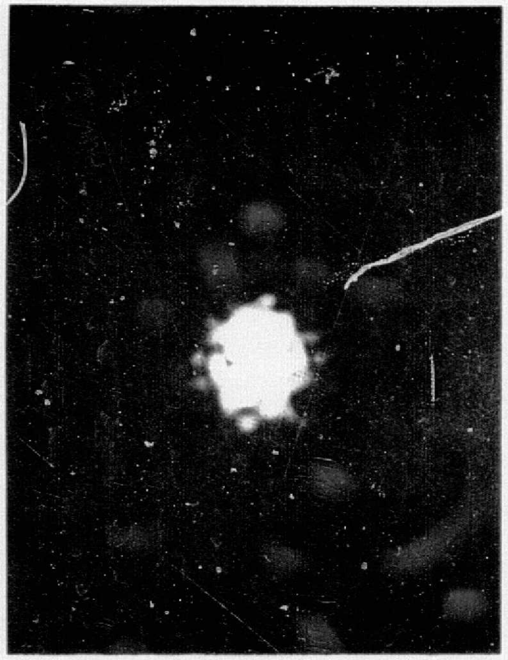
Test No. 2A
Retro: A
Photo No. 12
Exposure Time: 1/250 SEC

LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI

cm 1 2 3



Test No. 2A
Retro: B
Photo No. 13
Exposure Time: 1/250 SEC



Test No. 2A
Retro: C
Photo No. 14
Exposure Time: 1/250 SEC

Test No. 2A
Retro: CALIB
Photo No. 15
Exposure Time: 1/500 SEC

LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI

Test No. 2A
Retro: D
Photo No. 16
Exposure Time: 1/250 SEC

Test No. 2A
Retro: E
Photo No. 17
Exposure Time: 1/250 SEC

Test No. 2A
Retro: F
Photo No. 18
Exposure Time: 1/250 SEC

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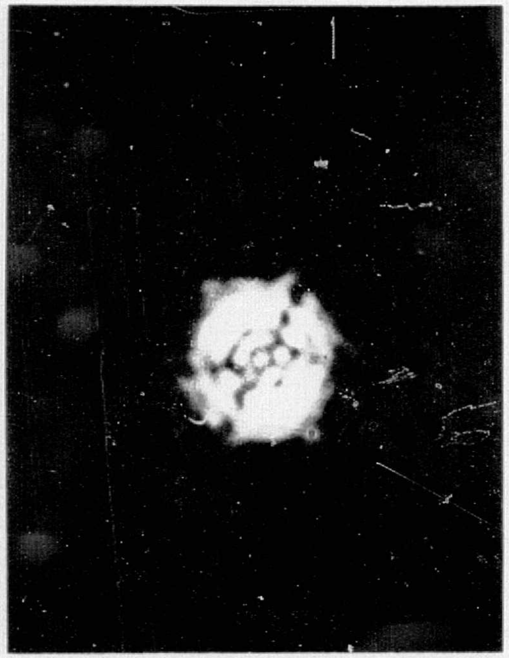
LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI



A-19

Test No. 2A
Retro: D
Photo No. 19
Exposure Time: 1/250 SEC

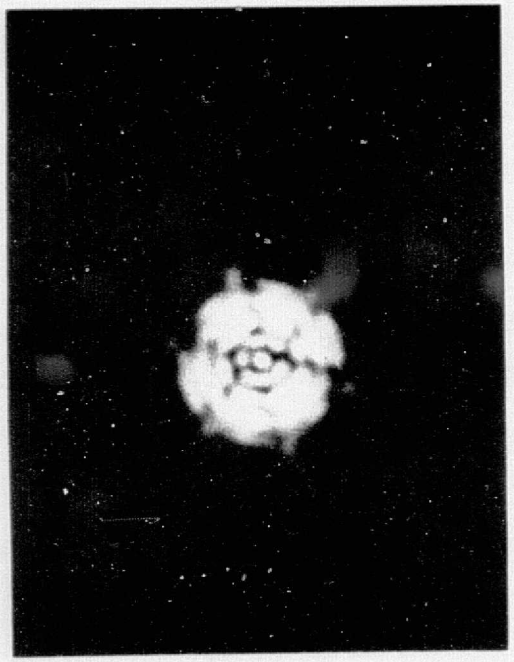
A-20

Test No. 2A
Retro: E
Photo No. 20
Exposure Time: 1/250 SEC

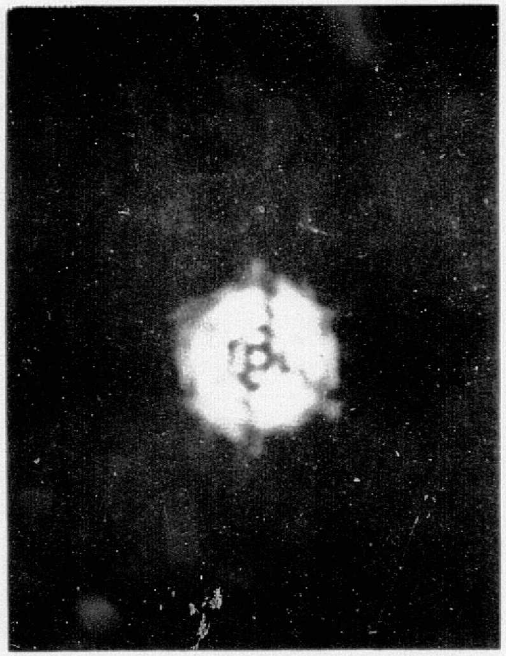
A-21

Test No. 2A
Retro: F
Photo No. 21
Exposure Time: 1/250 SEC

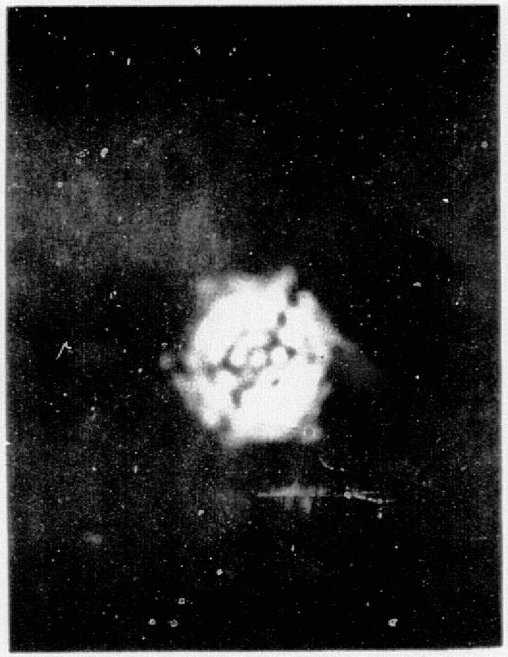
LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI



Test No. 3A
Retro: F
Photo No. 22
Exposure Time: 1/250 sec



Test No. 3A
Retro: E
Photo No. 23
Exposure Time: 1/250 sec



Test No. 3A
Retro: D
Photo No. 24
Exposure Time: 1/250 sec

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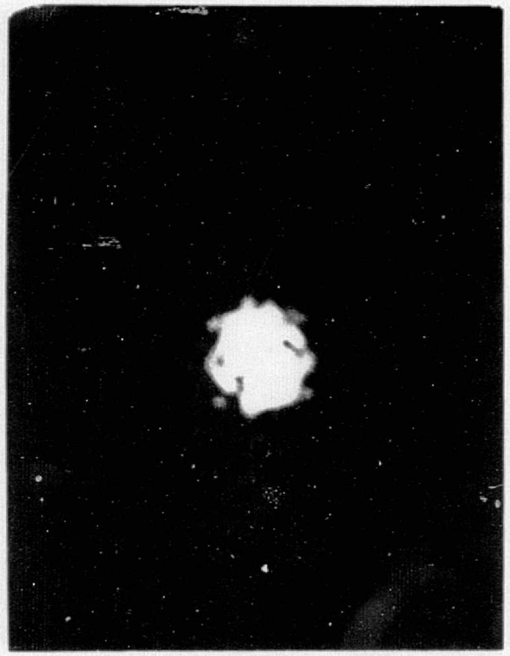
LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI

Test No. 3A
Retro: CALIB
Photo No. 25
Exposure Time: 1/500 SEC

Test No. 3A
Retro: C
Photo No. 26
Exposure Time: 1/250 SEC

Test No. 3A
Retro: B
Photo No. 27
Exposure Time: 1/250 SEC

LAGEOS THERMAL/OPTICAL TESTS
FAR-FIELD DIFFRACTION PATTERN
PHOTOGRAPHIC OUTPUT - FFDI



Test No. 3A
Retro: A
Photo No. 28
Exposure Time:

Test No. 3A
Retro: CALIB
Photo No. 29
Exposure Time:

Test No.
Retro:
Photo No.
Exposure Time: